SCHEDULING UNITS WITH MULTIPLE OPERATING MODES IN UNIT COMMITMENT

Arthur I. Cohen
ABB Systems Control
Santa Clara, CA

Gregory Ostrowski
Michigan Electric Power Coord. Center
Ann Arbor, MI

Abstract — **The operating flexibility of certain types of generating units can be exploited to reduce the production cost of their system. These units have different operating modes where the operating parameters can differ greatly depending which mode is operating at the time. Examples of such units are: combined cycle, fuel switching/blending, constant/variable pressure, overfire and dual boiler. A general modeling approach is described which can be used to model units with multiple operating modes. It is shown how Lagrangian relaxation can be used to schedule these units. Examples are given showing the benefit of using these methods to schedule a utility's system.**

1. INTRODUCTION

Certain types of generating units have different modes of operation where the operating parameters of the unit (e.g., unit limits, heat rates, ramp rates) can differ greatly depending upon which mode is operating at the time. There may be advantages in operating in different modes at different times. Therefore, the unit commitment problem, which historically has determined which units should be on at which times needs to be expanded to also determine which operating mode the units have to be in at each time.

Examples of units having different operating modes are:

- Combined Cycle
- Fuel Switching/Blending
- Constant/Variable Pressure
- Overfire
- Dual Boiler

Combined Cycle

Combined cycle units consist of one or more combustion turbines along with one or more waste heat boilers. The waste heat from the combustion turbines is fed into the boilers and steam from the boilers is used to run turbines. Both the combustion turbines and the steam turbines produce electric energy. Generally, the combustion turbines can be operated with the boiler (or boilers) or they can operate without the boiler. For a combined cycle unit with two combustion turbines (CT A and B) and one boiler, the following six combinations are typically possible.

- CT A
- CT B
- CT A and CT B
- CT A and Boiler
- CT B and Boiler
- CT A, CT B and Boiler

The modes with the boiler are more efficient with the last mode listed (both combustion turbines and the boiler) the most efficient. However, the modes with the boiler also have higher generating regions; therefore, for a certain mix of units and loads, it may be economic to generate using the modes with the boiler at certain times and to just use the combustion turbines to provide generation at other times. There are also conditions regarding the transitions between modes. These include:

- the combined cycle units must operate for a specified time period using only the combustion turbines prior to generating using the waste-heat boiler,
- there is usually a minimum required time to operate in each mode.

Fuel Switching/Blending

Fuel switching/blending units are units which can operate using different fuels or blends of fuels where the operating characteristics of the unit are a function of the fuels used. A typical example is a coal-fired unit that can burn either western or eastern coal where the western coal is lower in cost, quality (i.e., more ash, lower BTU/ton) and sulfur. The coal used affects the operating characteristics of the unit. The unit capability is lower for the western coal and the heat rate is different (higher and of a different shape). The cost curve is lower for the western coal due to the lower fuel cost. Therefore, although operating with the western coal is less expensive, it may be necessary to use the eastern coal for some fuel switching/blending units to provide additional generating capability. The transition between using one fuel (or blend) and another blend may take several hours. In addition, some units may be required to go off-line to change fuels.

Constant/Variable Pressure

Constant/variable pressure units are units which can change generation either under constant or variable pressure. The unit limits, ramp rates and heat rate can be affected by the control mode. Typically units can operate with lower generation while under variable pressure control; however, they cannot ramp as quickly. The transition between variable and constant pressure can only occur when the unit generation is below a given value.

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Overfire

Overfire units are units that can burn two fuels where the second fuel provides additional capability. The second fuel is assumed to be considerably more expensive. These units are typically coal units where either oil or gas supplies the overfire capability. The heat rate when using the overfire fuel can be quite different from the heat rate when the base fuel is used. Operating constraints can include a minimum time the base unit must be on before overfire operation can begin and a minimum time of overfire operation.

Dual Boiler

Dual boiler units are units consisting of two boilers where the steam from both boilers combines before feeding into the generating turbines. The heat rates and unit limits are a function of whether one or both of the boilers are operating. Typically one boiler must be operating for a given time prior to starting the second boiler and each boiler must operate for a minimum amount of time.

2. MODELING OF MULTIPLE CONFIGURATIONS

The above units can be modeled by allowing each unit to have multiple configurations where each configuration has its own set of unit parameters. We use the nomenclature "unit mod" or simply "mod" to denote one of the unit's configurations. It should be noted that modeling multiple configurations by modeling each configuration as a different pseudo unit is not new and can be done in any unit commitment program; however, the selection of which unit mod can operate at any time must be done manually. As we show using several examples, automating this selection is needed especially for systems that have several of these types of units.

We define two types of unit mods: dependent and exclusive. A unit mod is dependent if it can operate only if another specified mod is operating. An example of a dependent mod is the overfire operation of a unit; the unit cannot be in overfire mode unless the base unit is scheduled. Exclusive mods are mutually exclusive, that is, only one of the mods of the unit can operate at a time. An example of exclusive mods are the different configurations of a combined cycle unit. A dependent mod may be dependent on an exclusive mod; that is, the dependent mod may operate only if the specified exclusive mod is operating.

The remainder of this section describes the modeling of the dependent and exclusive mods. Unless otherwise stated all data related to a unit is defined at the level of the unit mod. Therefore each mod has its own unit limits, reserve parameters, ramp rates, startup and shutdown profile, heat rates, etc. Fixed generation, maintenance and deration also applies to unit mods.

2.1 DEPENDENT MODS

In addition to a full set of unit data, dependent mods also need to specify:

- base mod -- the unit or unit mod that must be on for this mod to be on.
- minimum on time of base mod -- the number of hours the base mod must be up before the dependent mod can be started.

It is assumed that the incremental cost curve for the dependent mod is greater than the curve for the base mod.

2.2 EXCLUSIVE MODS

Exclusive mods are defined by the allowed transitions between the mods and the allowed transitions between the mods and the off state. Also the unit corresponding to the exclusive mods is assumed to have a single minimum down time; that is, the time the unit must be down is independent of how the unit operated before it is down or will operate after it starts. The minimum up time of the mod corresponds to the time the mod must be on prior to the transition from the mod to the off state.

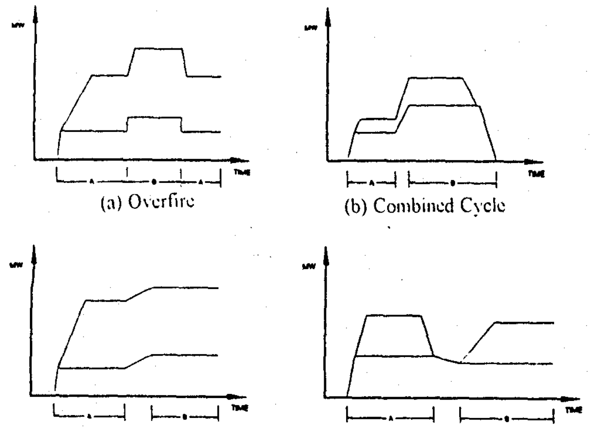
Additional data associated with an exclusive mod are:

- Startup flag -- indicates if the unit can startup from off into this mod
- Shutdown flag -- indicates if the unit can shutdown from this mod
- For each allowed transition:
  - "Prior Mod" -- the mod on prior to the transition
  - "After Mod" -- the mod on after the transition
  - Minimum up time -- the time the mod must operate prior to the transition
  - Low and high operating limits prior to the transition
  - Low and high operating limits after the transition
  - Transition time -- the number of hours it takes to transition between the mod and the associated after mod.
  - Transition ramp -- the ramp rate in MW/hour during the transition
  - Transition cost -- the cost of the transition in $/transition

The generation during the transitions is constrained as follows: If the transition time is greater than 0, then the transitioned limits are governed by the limits before and after the transition and the transition ramp rate. The unit data corresponding to the prior or after mod with the larger capability are used to define all other data (e.g., heat rate, reserve parameters) during the transition period. This choice, though somewhat arbitrary, was made because the reason the transitions occur is to provide the increased capability.

2.3 EXAMPLES

To aid in understanding the capabilities of the above modeling, Figure 1 shows sample generation capabilities of four units having different mods where the transition times are specified. The actual generation schedule must lie between the upper and lower lines. Figure 1a shows overfire operation where Mod A is the base mod and Mod B is the dependent mod. Figure 1b shows combined cycle operation where Mod A is the GT operating alone and Mod B is the GT operating with the waste heat unit. Figure 1c shows the case where the fuel mix is changed during the transition period where the unit limits depend on the mix. Lastly, Figure 1d shows constant pressure - variable pressure operation where the unit must be operating near its low limit during the transition.



(a) Overfire (b) Combined Cycle

(c) Fuel Switching (d) Variable/Constant Pressure

Fig. 1 - Example Generation Regions

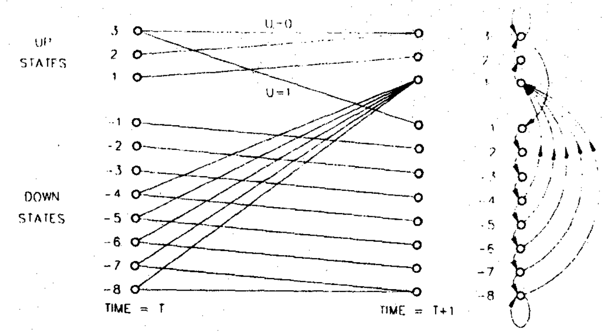


Fig. 2 - State Transition Diagram for Normal Unit

3. ALGORITHM FOR SCHEDULING UNIT MODS

The Lagrangian relaxation (LR) method [1-5] is used to schedule the unit mods. Recall that the LR method solves the unit commitment problem by decomposing it into a set of single unit problems where the system constraints (constraints involving more than one unit such as the load and reserve constraints) are adjoined onto the cost using Lagrange multipliers. The set of single unit problems are solved repeatedly where the Lagrange multipliers are adjusted in each iteration so that the method converges to a near-optimal feasible solution to the unit commitment problem. The modeling of the unit mods only affects the single unit problems; therefore, please refer to the above-mentioned references for further information regarding the overall LR method.

The single unit problems involve minimizing the dual cost subject to constraints on unit generation, minimum up and down time, and ramp rates where the dual cost includes generation cost, startup cost and terms containing the Lagrange multipliers. Dynamic programming is used to solve the single unit problems because of its ability to model time-dependent startup cost and non-convex constraints such as minimum up and down time. Defining the dynamic programming problem requires defining the possible states that the unit can be in at each time point and defining the transitions between states. For the standard unit commitment problem, the state space consists of the hours the unit has been up and down. This leads to an equation of the form:

$$x_i(t+1) = f(x_i(t), u_i(t))$$

where $x_i(t)$ is the state number of hours on or off at time t for unit i and $u_i(t)$ is the control (either 1 for on or 0 for off). For convenience we define positive values of x to denote on hours and negative values to denote off hours). For example, if the unit is in state 10 (unit on for 10 hours) in hour t and the unit is scheduled on ($u_i(t) = 1$), then the state in t+1 will be 11; if the unit is scheduled off ($u_i(t) = 0$) then the state in t+1 will be -1 (unit down 1 hour). Note, there is no need to keep track of the unit being on greater than the minimum up time or for units being off longer than the maximum of the minimum down time and the time it takes the unit to cool down (so there is no effect on startup cost). Therefore, the state space is limited by these values. It is convenient to describe the allowed transitions using a state transition diagram; two forms of the diagram are shown in Figure 2 (this example assumes a minimum up time of 3 hours, a minimum down time of 4 hours and that the startup cost is independent of time the unit is down for down times greater than or equal to 8 hours).

3.1 OPTIMIZING EXCLUSIVE MODS

Exclusive mod units are modeled by defining the state space to include states to model:

- the time the unit is down
- for each mod that can be started from off, the time the mod has been on
- for each mod that can transitioned to from another mod, the time the mod has been on
- for each transition, the time the unit is in the transition period

Modeling separate sets of states to correspond to the cases where the unit is (1) in transition, (2) the unit is started from off, and (3) the unit is transitioned from another mod, allows the consideration of how the unit limits vary with how long the unit has been in each of these operating modes.

Consider the case of a unit with two exclusive mods A and B where each mod can transition to the other and where the unit can startup in either mod. Then the state diagram for this case can be illustrated as shown in Figure 3 where each bubble contains a number of states corresponding to the time the unit is in that state and the arrows indicate the allowed transitions between groups of states. In the diagram, D denotes the down states, A and B denote states corresponding to mods that start from off, A* and B*, denote states corresponding to mods that start from another mod, and Tab and Tba denote transitions between mods. Figure 4 expands Figure 3 to show the transition diagram for all the states for this example.

Once the state space and transitions are defined, then dynamic programming can be used to solve the single unit problems in exactly the same way as for regular problems. The remainder of the LR method for optimizing exclusive mods is identical to the standard LR method.

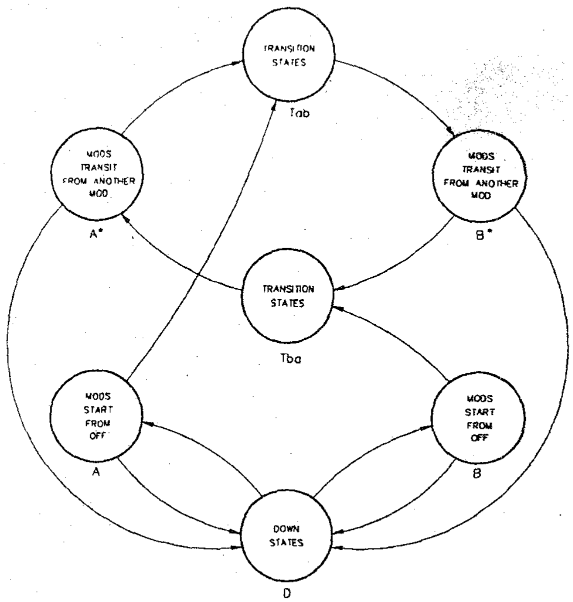


Fig. 3 - Transition Between Unit Mods

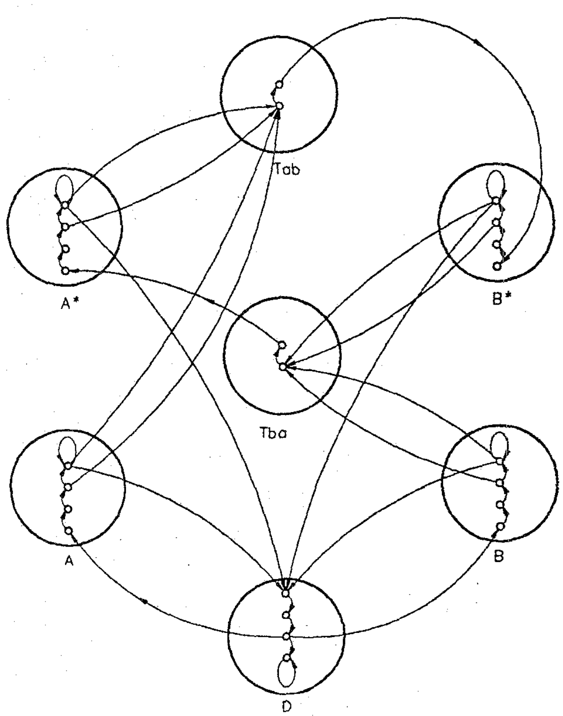


Fig. 4 - State Transition Diagram for Unit with Mods

3.2 OPTIMIZING DEPENDENT MODS

Dependent mods are optimized using a straightforward modification of the standard LR method. The dependent mod is modeled as an additional regular unit and is optimized the same as a regular unit with the following constraints:

- The single unit problem for the dependent mod unit is done after the single unit problem for the base unit.
- When solving the single unit problem for the dependent mod unit, require that the base unit must have been on for the specified time needed for the dependent mod to be on.

4. EXAMPLES

The following examples show the effect of including unit mods in unit commitment. Two sets of examples will be shown, the first demonstrates the scheduling of units with fuel switching and overfire capability and the second demonstrates the scheduling of combined cycle units.

4.1 FUEL SWITCHING

The utility in this example has 13 units where one unit (PALO UN2) is an overfire unit and two other units (ALTOS UN3 and ALTOS UN4) are fuel switching units. The unit mod limits, minimum up and down times and average cost at the high limits are shown in Table 1.

TABLE 1 - UNIT DATA FOR FUELING SWITCHING EXAMPLE

UNIT MOD NAME	LOW LIMIT (MW)	HIGH LIMIT (MW)	AVG. COST ($/MWH)	MIN. UP TIME	MIN. DOWN TIME
PALO UN1	150	325	33.24	5	3
PALO UN2 A	250	550	18.29	5	3
PALO UN2 B	25	82	24.89	4	
ALTO UN1	25	82	35.29	4	15
ALTO UN2	50	102	31.96	5	3
MENLO UN1	25	75	29.54	3	2
MENLO UN2	25	78	32.96	3	2
PARK UN1	25	64	34.53	6	40
PARK UN2	25	64	35.61	6	40
PARK UN3	80	180	27.27	3	2
PARK UN4	50	176	43.51	5	5
ALTOS UN2	150	560	31.05	72	25
ALTOS UN3 A	150	555	19.16	5	3
ALTOS UN3 B	120	450	17.38	5	
ALTOS UN4 A	150	555	19.16	5	3
ALTOS UN4 B	120	450	17.38	5	

The "A" and "B" appended to the end of the unit names differentiate the unit mods. PALO UN2 A is the base mod and PALO UN2 B is the dependent mod; PALO UN2 B can only be on if PALO UN2 A is on. ALTOS UN3 A and B are the two exclusive mods of the fuel switching unit; ALTOS UN3 A uses the better quality and more costly fuel. Table 1 shows that ALTOS UN3 A has both higher generation capability and runs at higher cost. ALTOS UN4 is identical with ALTOS UN3.

The ALTOS UN3 mods can be started from off in either mod A or B and shut down from either mod A and B. Transitions are allowed from mod A to mod B and from mod B to mod A. The transition times in both directions are 3 hours. The transition characteristics of ALTOS UN4 are identical with ALTOS UN3.

Three 24 hour unit commitment cases (Cases 1-3) are run. Case i+1 has the same conditions as Case i except the load is increased in each case.

Case 1

The Figure 5 shows the schedule for this case; the dark bars denote on units while the light bars denote off units. Note that only units PALO UN2 and ALTOS UN3 and ALTOS UN4 are on. For the overfire unit PALO UN2, the overfire mod (B) is on for hours 14 through 19. The fuel switching units (ALTOS UN3 and ALTOS UN4) are operating in mod B which corresponds to them using the less expensive fuel.

One may question why the overfire mod is used in unit PALO UN2 instead of using the more expensive fuel in ALTOS UN3 since the average cost of ALTOS UN3 A is 19.16 $/MWH while the average cost of PALO UN2 B is 24.89 $/MWH. The reason is that all the generation for the unit ALTOS UN3 has to be at the higher cost fuel. The following example compares the cost of two cases where we assume the average cost at the high limit can be used to calculate the cost at other generations.

	USE OVERFIRE		DO NOT USE OVERFIRE	
	GEN (MW)	COST ($)	GEN (MW)	COST ($)
PALO UN2 B	50	1245		
ALTOS UN3 A			500	9580
ALTOS UN3 B	450	7821		
TOTALS:	500	9066	500	9580

This shows that the cost of switching to the more expensive fuel is much greater than comparing the average costs would indicate.

Case 2

Case 2 is generated by adding 50 MW to the load in each hour. The unit schedules, given in Figures 6, show that for this case it is economic for ALTOS UN3 to switch to the more expensive fuel for the peak hours.

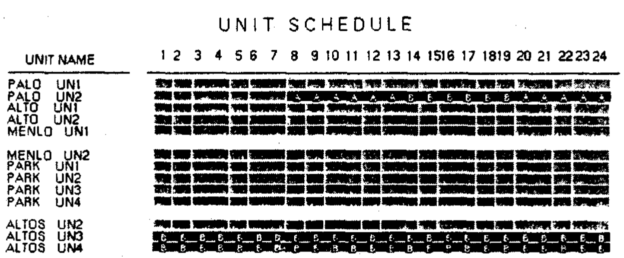


Fig. 5 - Case 1 - Fuel Switching

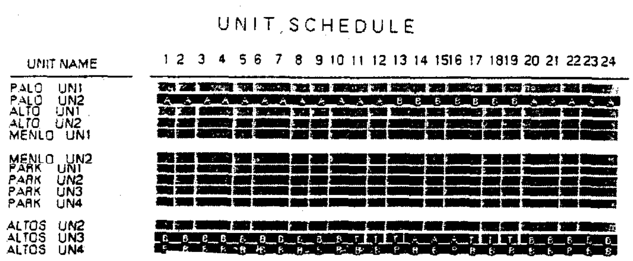


Fig. 6 - Case 2 - Fuel Switching

Case 3

Case 3 is generated by adding 150 MW to the Case 1 load in each hour. The unit schedules, given in Figure 7, show that PARK UN3 is brought on to meet the peak load and ALTOS UN3 is now using the less expensive fuel. Therefore, for this case, it is better to use PARK UN3 with an average cost of over $27 instead of switching both fuel switching units to the more expensive fuel.

4.2 COMBINED CYCLE UNITS

The utility in this example also has 13 units. In this case, one unit (PALO UN1) is an overfire unit where the overfire portion is unavailable. Two units (ALTOS UN1 and ALTOS UN2) are combined cycle units. The unit mod limits, minimum up and down times and average cost at the high limits are shown in Table 2. The letters "A" - "D" appended to the end of the unit names differentiate the unit mods for the combined cycle units. ALTOS UN1 and ALTOS UN2 are identical. The mods correspond to the following unit configurations:

MOD	DESCRIPTION	START	SHUTDOWN
A	CT 1 & CT 2 & Boiler	N	Y
B	CT 1 & Boiler	N	Y
C	CT 1	Y	Y
D	CT 1 & CT 2	Y	Y

where CT 1 and CT 2 are the two combustion turbines and Y/N indicate whether the unit mod can start from off and shutdown to off. The allowed transitions and transition times are shown below.

PRIOR MOD	MINIMUM UP TIME (HR)	AFTER MOD	TRANSITION TIME (HR)
A	4	B	1
A	4	C	1
A	4	D	1
B	4	C	1
C	2	B	1
C	2	D	1
D	2	A	1
D	2	C	1

The minimum up time is the time the prior mod must be on-line prior to transitioning and the transition time is the time it takes to transition from one mod to the other. From the above tables, one observes that one or both combustion turbines must be on before starting the waste heat boiler.

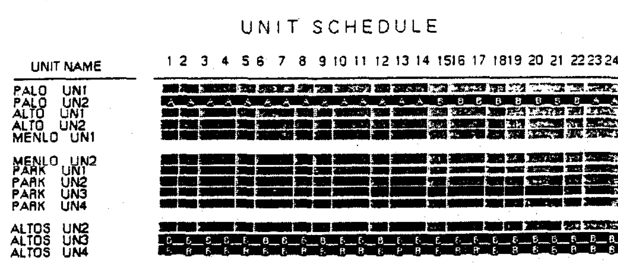


Fig. 7 - Case 3 - Fuel Switching

TABLE 2 - UNIT DATA FOR COMBINED CYCLE EXAMPLE

UNIT MOD NAME	LOW LIMIT (MW)	HIGH LIMIT (MW)	AVG. COST ($/MWH)	MIN. UP TIME	MIN. DOWN TIME
PALO UN1	150	325	23.54	5	3
PALO UN2 A	250	550	29.16	5	3
ALTO UN1	25	82	24.89	4	15
ALTO UN2	50	102	21.96		
MENLO UN1	25	75	26.00	3	2
MENLO UN2	25	78	22.39	3	2
PARK UN1	25	64	24.30	6	40
PARK UN2	25	64	25.02	6	40
PARK UN3	80	180	27.27	3	2
PARK UN4	50	176	30.71	5	5
ALTOS UN1 A	100	200	19.59	5	3
ALTOS UN1 B	50	100	20.82	5	
ALTOS UN1 C	25	82	24.89	4	
ALTOS UN1 D	50	164	24.89	4	
ALTOS UN2 A	100	200	19.59	5	3
ALTOS UN2 B	50	100	20.82	5	
ALTOS UN2 C	25	82	24.89	4	
ALTOS UN2 D	50	164	24.89	4	
ALTOS UN3	150	560	19.01	72	20

Four 24 hour unit commitment cases (Cases 1-3) are run. Case i+1 has the same conditions as Case i except the load is increased for each case. In all the cases PALO UN2, PARK UN3 and ALTOS UN3 are forced to be on for every hour.

Case 1

The schedules for this case is shown in Figure 8. ALTOS UN1 starts with both CT's on and then starts the boiler while ALTOS UN2 just used CT 1 as a peaker.

Case 2

Case 2 is generated by adding 50 MW to the Case 1 load in each hour. Figure 9 shows the unit schedules for this case. ALTOS UN1 starts with both CT's on and then starts the boiler while ALTOS UN2 first uses CT 1 as a peaker and then turns on the boiler.

Case 3

Case 3 is generated by adding 100 MW to the Case 1 load in each hour. Figure 10 shows the unit schedules for this case. ALTOS UN1 starts with a single CT on then switches to putting both CT's on prior to starting the boiler. ALTOS UN2 operates similarly to ALTOS UN1 with the only difference being that it starts later in the day.

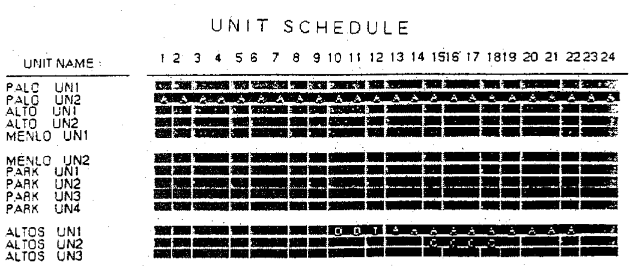


Fig. 8 - Case 1 - Combined Cycle

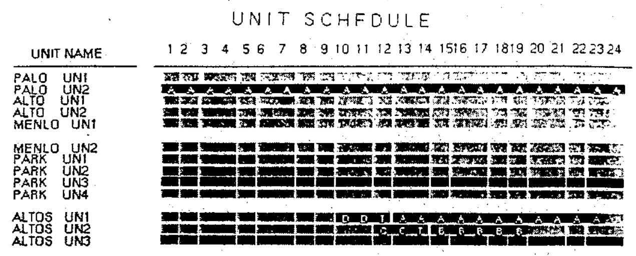


Fig. 9 - Case 2 - Combined Cycle

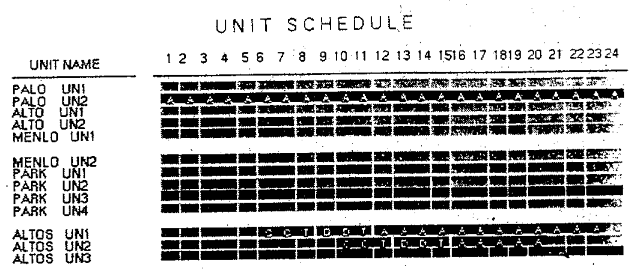


Fig. 10 - Case 3 - Combined Cycle

5. CONCLUSION

A detailed model has been presented which can be used to model units whose operating characteristics vary with their operating mode. It has been shown how any Lagrangian relaxation unit commitment algorithm can be modified to determine how to schedule a power system that includes such units. The examples presented show that the manner that a unit with multiple configurations is used, if operated optimally, can be a strong function of the load and the other units available. The additional computer time required to schedule a unit with multiple configurations depends on the number of configurations, the number of transitions, the minimum up times and the transition times. A unit with n configurations will typically take about $2n$ times the time required to schedule a unit with one configuration.

These new modeling techniques are being developed for the Michigan Electric Power Coordination Center (MEPCC). MEPCC has responsibility for scheduling the generation within Michigan for Detroit Edison and Consumers Power Companies. MEPCC units include a number of large generation units that can burn different kinds of coal. These units also have overfire capability. The evaluation of which fuels to use in which units has become a difficult task due to the fact that the operating characteristics are dependent on the fuels used. MEPCC expects that including the ability to schedule the operating mode of these units will better enable the system schedulers and operators to operate the power system economically and in a way that meets environmental restrictions.

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BIOGRAPHIES

Arthur I. Cohen (Member, IEEE) received the B.S. and M.S. degrees in Electrical Engineering from Cornell University and the Ph.D. degree from the University of California, Berkeley. He is a Senior Principal Consultant at ABB Systems Control, Santa Clara, California. He has received the William Bendix Automotive Electronics Award for his work in developing controls for cold engine operation. He is currently interests are in developing methods for resource scheduling in the electric power industry.

Gregory J. Ostrowski received the B.S.E.E. degree from Wayne State University and the M.S.E.E. degree from the University of Michigan. He is a Principal Engineer for Detroit Edison Company. He currently works at the Michigan Electric Power Coordinating Center, Ann Arbor, Michigan, where he is responsible for the system power transactions as well as the daily planning and scheduling of the generation units of the combined systems of Detroit Power and Consumers Power Companies. He is a Registered Professional Engineer in Michigan.