

Solving Unit Commitment Including Wind Power Generation Using PSS®E

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Abstract: Operating the power system in optimal way and keeping it safe and reliable is very important in power systems planning and operation. The power system currently has a large variety of power plants that operate with different kinds of fossil fuel or use renewable energy to produce power. As the demand on electricity is fluctuated, utilities are obligated to provide consumers with power at any time during a day. Power system operators try to supply electricity in an economic operation by turning on the cheapest generating units and turning off the most expensive ones at off-peak value of the load. Finding the optimal combination of units to supply forecasting load is called unit commitment problem (UC). The second step of the optimization problem is finding the optimal output power from each committed unit, which known as economic dispatch (ED). The main benefits of solving the unit commitment problem and economic dispatch are to minimize generation cost over the objective period horizon while applying all system constraints that come from generating units' limits and the transmission system's characteristics, as well as to verify the balance between power generation and power demand. While, the optimal power flow (OPF) tries to find the optimal dispatch for the whole power system, but by taking into account all systems constrain, such as voltage security and transmission line limit. The optimal power flow can control many variables to find the optimal operation of the system, like a transformer tap changer, phase shifter, switched shunt, and load adjustment. In this paper, power system simulator for engineering (PSS®E) is used to solve unit commitment, economic dispatch, and optimal power flow. The implementation is performed on IEEE 30-bus system for a 24-hour period. In the first stage, the UC, ED, and OPF were solved for the systems without including wind power generation. In the second stage, UC, ED, and OPF were solved by including a wind-power farm with 100 MW rated power connected to the system. The solution is based on 24-hour wind data forecasting, and 24-hour power demand's prediction.

Keywords: Unit Commitment, Optimum power flow, Economic Dispatch, Wind Generation, PSS®E, data forecasting

1. Introduction

The world is fully dependent on electricity these days. Electrical energy provides light, transportation, communication, cooling, heating and industry. Its share is about 20% of energy in the world [1]. Power systems currently are no longer separated systems. They are now tied together to form huge interconnected systems to increase the reliability of the power system. However, this makes the power system more complicated and shows many challenges regarding control and security of the system. Power systems in reality, comprises of three main interdependent sub-systems: Generation, Transmission and Distribution systems. Generation generates electrical power using different power generation ways: Thermal plants that use fossil fuel like gas, oil or coal, nuclear plants use uranium or plutonium, and renewable energy which depends on wind, sun, tide or geothermal sources. Transmission transfers power with high voltage (up to 750 KV to reduce the power losses that happen in transmission lines due to (I².R)) from power plants to power distribution substations. A distribution which is usually located near the load center supplies power to consumers with low voltage. Each of these sub-system works with different constraints and bindings which affect the whole system operation. Because of fast increasing

demand on the electricity due to the world expands, every utility is trying to solve the problem of reliability of the system, and at the same time, run the power system in economic operation.

Power consumption changes continuously during a day or during a year based on human requirements. It varies from a base load to peak load. The power system operators are obligated to supply all load areas at any time. Therefore, they need to run more enough number of generators to meet demand at peak period. Owing to the high cost of fuel, these generators have to be turned off during the off-peak period. The decision of scheduling generation units optimally to be ON\OFF to satisfy the operational needs of the system is known as unit commitment (UC) [2]. The power system's generation has a variety of power plants that run by different types of fuel, or those plants that use renewable energy, which have the lowest operating cost. The most efficient units are connected to the system first and followed by the units that have less efficiency to supply the forecast or predicted power demand of the system over a future time period, varying from several hours to a week [3]. The main benefit of solving the unit commitment problem is to minimize generation cost over the objective period horizon while applying all system constraints that come from generating units' limits and the transmission system's characteristics. Basically, some of the generating units have limitations such as ramp-rate limits [4], minimum up and down time limits [5], fuel constraints [6] as well as maximum and minimum generation limits [7]. The transmission grid also plays major role in constraining UC [8]. The transmission line has a certain limit of current able to carry. It cannot be exceeded, otherwise the line melts. Unit commitment problem consists of two stages. The first stage is to schedule generating units when and how long to be ON\OFF, and the second one is named as Economic Dispatch (ED), which calculates the optimal amount of generation that each unit must supply. Units consume different types of fuel, and each type has its own characteristics and cost. Therefore, the generation cost is linked to amount of power each committed unit produces.

2. Unit Commitment literature review

UC is a nonlinear optimization problem in power system operation. Due to the increasing expansion in the power system, finding the solution for UC becomes more exhaustive and combinatorial, especially in the presence of uncertain data, like outage contingencies of units, as well as forecasting error of demand and renewable energy. Many methodologies and techniques have been presented to solve UC problem over the last a few decades. Methodologies and techniques used to solve UC problem include deterministic methods such as the priority list (PL), Integer Programming (IP), Mixed Integer Programming (MIP), Dynamic Programming (DP) The Branch and Bound (BB), and Lagrangian Relaxation (LR). Deterministic approaches in somewhat are simple, but they have some disadvantages like result accuracy, and the time need to execute. The second approaches are stochastic optimization algorithms, which include Evolutionary Programming (EP), Artificial Neural Networks (ANN), Genetic Algorithms (GA), Ant Colony Optimization (ACO), Simulated Annealing (SA), Particle Swarm Optimization (PSO), and Tabu Search (TS). The third approach is hybrid techniques, which based on deterministic and stochastic approaches. It combines two or more of optimization techniques that mentioned above. The benefits of hybrid of two or more methods is to shorten the execution time and to improve the equality [11, 12].

2.1 Deterministic Approaches

2.1.1 Priority List

The priority list is pretty simple and takes a short time for computing. It needs a small computer memory. However, the solution of the UC using the priority list is not the optimal solution because the ramp rate constrains and start-up cost are not satisfied in the priority list method. An Extended Priority List (EPL) method was introduced in [13] to solve unit commitment problems. The EPL technique contains two steps. In the first step, it proposes a fast start of UC problem schedules using the priority List (PL) method by disregarding operational constraints. In the second step unit schedule is improved using the problem specific heuristics to satisfy operational constraints. An evolutionary algorithm (EA)

with problem specific heuristics and genetic operators was proposed in [14] to solve the unit commitment problem. The initial random population is seeded with good solutions using a priority list method to increase the speed of convergence and make the algorithm more efficient.

2.1.2. Dynamic Programming

DP to solve a unit commitment problem was proposed by P. G. Lowery in 1966, [15]. The method was trying to determine the feasibility of using Dynamic Programming to solve the UC. As the computing processing was not as it is today, the method faced the main difficulty of computing the large number of factorial N, even for a small number of units. In 1979, Pang, et al [16] presented a truncated dynamic programming method for the commitment of thermal units over the periods of up to 48 hours. They included operating constraints and spinning reserve requirements in UC problem. In 1981, Pang, et al. [17] compared the operation of four unit commitment methods. Three of them were based on the DP, and the fourth one was based entirely on a priority list. The paper also dealt with the modeling of inter-area flow constraints by the inter flow network. The paper in [18] presented a Mixed Integer-Linear (MIL) and Dynamic Programming to find the power-generation scheduling and improve the algorithm. MIL is used to specify feasible combinations of units at each scheduling point. A new dynamic programming approach determines scheduling routes. The solutions were similar to MIL programming with saving execution time and computer memory. W. L. Snyder, et al. In [19], presented a field-proven dynamic programming formulation of the unit commitment problem. The approach was to classify generating units into related groups in order to reduce the number of unit combinations that need to be tested including the optimal path at first. In [20] a new approach has been developed to improve dynamic programming by saving predecessor options. This approach was implemented in an on-line energy management system. The method supports realistic modeling of unit start-up ramps as well as it analyses solution paths that might be eliminated under traditional methods. Z. Ouyang, et al. [21], presented a heuristic improvement of the truncated window dynamic programming (DP-VW). The proposed method uses a variable window size according to load demand increments. The experimental results show significant saving in the computation time without losing the quality of the solution.

2.1.3. Branch and Bound

A new approach is proposed in [22] based on branch-and-bound technique. The method incorporates start-up costs, load demand, spinning reserve, MUT and MDT constraints, and it can be extended to allow for a probabilistic reserve constraint. It does not need a priority ordering of the units. In [23], a new branch-and-bound algorithm for the unit scheduling problem was presented. This efficient branching method based on the 'heap' data structure and a simple intuitive binding rule. Computational results show that the proposed approach generates the optimum schedule in less time comparing with many other techniques.

2.1.4. Integer and Mixed Integer programming

In 1968, John A. Muckstadt et al. [24] presented a decomposable mixed integer programming model for simultaneous economic consideration of unit commitment and short-term dispatch of thermal units. The method characterizes demand forecast as a discretized function to be incorporated in the scheduling model, permitting a probabilistic forecast. In 1978, T. S. Dillon et al. in [25] developed a method to determine UC schedule for hydro-thermal systems using extensions and modification of Branch and Bound method for integer programming. The main features of this method are being computationally practical for realistic system. Besides, the method represents reserves with different risk levels. S. Takriti, et al. [26] presented a technique for refining solution of scheduling unit commitment by solving the Lagrangian. It uses a mix integer program to improve the solution, and then it is solved by using branch-and-bound to the optimal solution. The method indicates a significant improvement in the quality of the solution for large a number of units. The paper in [27], formulated the price-based unit commitment problem based on the mixed integer programming (MIP) method. The proposed PBUC solution is for a generating company (GENCO) which has combined-cycle, cascaded-hydro, and thermal pump storage units. The PBUC was solved by using MIP and was compared with that of Lagrangian relaxation (LR) method. Results indicate the advantages and efficiency of MIP

formulation for solving PBUC. However, solving a system with a large number of units by using MIP faced serious problems of computing time and memory, indicating the need for improving MIP formula, using a specific structure of UC problems or employing parallel processing. The advantages of using the fuzzy optimization was proved in[28]. This fuzzy linear optimization formulation of unit commitment is solved by exploitation of a mixed integer linear programming (MILP) routine. In this formulation, start-up cost is modeled using linear variables. The fuzzy formulation gives modeling flexibility, relaxation in constraint enforcement and allows the method to look for a practical solution.

2.1.5. Lagrangian relaxation

A new Lagrangian relaxation method to obtain the optimal solution was proposed in[29]. Numerous enhancements were envisaged to get the algorithm flexible such as simultaneous management of pumping units, probabilistic determination of the spinning reserve and so on. In [30] a new Lagrangian relaxation algorithm for unit commitment was proposed. The algorithm has three stages. The Lagrangian dual of UC was maximized with sub-gradient techniques in the first stage. Reserve-feasible dual solution was found in the second stage, then computed the economic dispatch in the third stage. The algorithm was tested on systems of up to 100 units to be scheduled over 168 hours, proving a reliable performance and short computing time. The algorithm also considered spinning and time-limited reserve constraints. In 1995, Baldick [31] formulates a generalized version of the UCP that can meet the most constraints such as the minimum up and down-time constraints, power flow constraints, reserve constraints, voltage limits, line flow limits, ramp limits, and total fuel and energy limits on hydro and thermal power generation units. The algorithm is based on Lagrangian decomposition. An enhanced adaptive Lagrangian relaxation (ALR) is proposed in[32]. The method contains adaptive LR (ALR) and heuristic search. ALR is enhanced by presenting a new 0-1 decisions criterion. After the ALR, the best feasible schedule is obtained, the heuristic search consisting of unit substitution and unit decommitment is used to fine-tune the solution. The total system production costs are less for the large-scale system. The execution time is much less compared with other approaches. In addition, ELR total system production costs are less expensive for a large system than others. The paper in [33] proposed a new algorithm based on the surrogate Lagrangian relaxation method to resolve the lower bound issue with convergence guaranteed. The method idea is examining the different behaviors of the algorithm as the optimal dual value is overestimated or underestimated. Testing results on manufacturing scheduling problems show the effectiveness of the algorithm.

2.2. Stochastic optimization algorithms approaches

2.2.1. Tabu search

In [34] an application of the Tabu Search (TS) method to solve the unit commitment problem (UCP) has been presented. Feasible UC schedules are generated randomly using new proposed rules. The problem has two subproblems. The first subproblem is a combinatorial optimization problem, and the second subproblem is a nonlinear programming problem. Numerical results show an improvement in the quality of the solution compared with other approaches.

2.2.2. Simulated annealing

Zhuang, et al. [35] proposed a general optimization method, known as simulated annealing, which is applied to generation unit commitment. The method generates feasible solutions randomly and moves among these solutions using a strategy leading to a global minimum with high probabilities, by utilizing the resemblance between a minimization process and the cooling of a molten metal. The method assumes no specific problem structures and is highly flexible in handling unit commitment constraints. The application of parallel simulated annealing for unit commitment problems has been investigated in this paper[36]. Speculative computation and serial subset are used to solve UCP of ten thermal generators depending on two parallel simulated annealing concepts. The paper also proposes a combined scheme which speculative computation is used in the initial phase, and the serial subset is utilized in the final stage. Results indicate that the parallel schemes can significantly speed up the computation of simulated annealing. A new simulated annealing (SA) algorithm combined with a dynamic economic

dispatch method has been developed by D. N. Simopoulos, et al. [37] for solving the short-term unit commitment (UC) problem. A dynamic economic dispatch method is exploited to incorporate the ramp rate constraints in the solution of the UC problem. New rules connecting with the tuning of the control parameters of the SA algorithm are also proposed. Numerical simulations have demonstrated the effectiveness of the presented algorithm in solving large UCP within a reasonable execution time. Saber, et al. in [38] proposed a new approach to UCP using stochastic simulated annealing method. A solution is chosen with a certain probability each iteration. A higher cost feasible solution is accepted with temperature-dependent probability when using simulated annealing method. Other solutions might be accepted deterministically which probably lead to the near optimization slowly. Numerical results show an improvement in solution cost and time compared to the results obtained from other algorithms.

2.2.3. Artificial Neural Network (ANN)

Sasaki, et al. [38] explore the possibility of applying the Hopfield neural network to combinatorial optimization problems in power systems. An exact mapping of the problem onto the neural network is not possible with the state of the art; therefore, a two-step solution method was developed. The first step is that generators to be stored up at each period are determined by the network. The second step is that their outputs are adjusted by a conventional algorithm. The proposed neural network could solve a large-scale UCP with up to 30 generators during 24 horizons, and the results obtained were very encouraging. H. Daneshi, et al. [39] presented a unit commitment method based on artificial neural network (ANN) and fuzzy dynamic programming (FDP). Comparison was made between ANN methods and FDP method. The results show that ANN algorithm has considerably reduced the execution time in UC based on binary codes. In the other side, the fuzzy approach achieves an acceptable operation cost and optimum state for constrained power systems.

2.2.4. Evolutionary Programming (EP)

Juste, et al. [40] proposed an algorithm exploits the evolutionary programming (EP) technique in which populations of contending solutions are evolved randomly. UC schedule is coded in this algorithm as a string of symbols and displayed as a candidate for reproduction. The practical implementation of this procedure obtained reasonable results by using the EP-based algorithm to solve UC problem comparing with existing techniques such as genetic algorithms (GAs), Lagrange relaxation (LR), and dynamic programming (DP). An evolutionary programming based tabu search method proposed to solve UCP in [41]. Evolutionary programming is designed to encode each unit's operating schedule with regard to its minimum up/down time by coding UC schedule as a string of symbols. The method generates an initial population randomly where each schedule is performed by committing all the units according to their initial status ("flat start"). The Tabu Search is used in this method to improve the status by avoiding entrapment in local minima.

2.2.5. Genetic Algorithm (GA)

A genetic approach for determining the priority order in the commitment of thermal units in power generation has been presented by D. Dasgupta et al. in [42]. The feasibility of using genetic algorithms was examined in this paper, and some simulation results were reported in the near optimal commitment of thermal units. In [43], Genetic Algorithm by utilizing Varying Quality Function technique and adding problem specific operators was implemented. This approach managed to obtain satisfactory solutions to the unit commitment problem. This paper also reported test results for 100-unit power system and comparison with other UCP methods. A new solution to the thermal unit-commitment (UC) problem based on an interger-coded genetic algorithm was presented by Damousis, I.G., et al. in [44]. The significant chromosome size reduction was achieved by the proposed coding compared to the usual binary coding. Consequently, execution time and robustness of the algorithm are improved. Besides, generating unit constraints such as the minimum up and minimum downtime are directly coded in the chromosome. As a result, the use of many penalty functions which distort the search space has been avoided. In this paper [45], a hybrid algorithm concept which integrates genetic algorithm (GA) combined with the principle of tabu search (TS) and priority list (PL) has been introduced to solve the unit commitment problem. Each method has to do a certain job. Solving the unit commitment problem will be

done by PL. The economic dispatch problem will be solved by GA and the principle of TS. The test results show that the total cost of the unit commitment problem that found by the proposed hybrid method is better than other comparable methods and near optimal solution.

2.2.6. Particle Swarm Optimization (PSO)

Z. L. Gaing, [46]introduced integrating a discrete binary particle swarm optimization (BPSO) method with the Lambda-iteration method to solve unit commitment (UC) problems. This method divided the unit commitment problem into two sub-problems. The first sub-problem is the unit scheduling problem which is solved by the BPSO method for the minimization of the transition cost, and the second sub-problem is ED, which is solved by using Lambda-iteration method for the minimization of the production cost. The simulation results show that this method is can obtain higher-quality solutions. Jin Lang, et al [47]proposed an improved binary particle swarm optimization algorithm (IBPSO) to solve short-term thermal unit commitment. The paper suggested two strategies to enhance the binary particle swarm optimization algorithm which are asynchronous time-varying learning strategy and a new repairing strategy for particles.

2.2.7. Ant Colony Optimization (ACO)

In-Keun Yu, et al. [48]proposed a new co-operative agent approach which is the Ant colony Search Algorithm (ACSA), to solve a short-term generation scheduling problem of a thermal power system. The goals were to demonstrate the applicability of an alternative intelligent search approach in the optimization of a power system. The ACSA inspired from ant colonies searching for food sources. The proposed scheme has demonstrated the effectiveness of the daily scheduling problem of a model power system comparing with those obtained by other scheduling methods. Sisworahardjo, N. S. in[49], presented an ant colony search algorithm (ACSA)-based approach to solve UCP. The algorithm is a population-based approach that exploits the positive feedback, distributed computation and constructive greedy heuristic. For best solutions, positive feedback is used. To avoid early convergence, distributed computation is exploited. And finding adequate solutions in the early stages of the search process the greedy heuristic is used. The ant colony search algorithm was found by inspiration of the natural behavior of the ant colonies on how they search and find the food source and bring them back to their nest by creating the unique trail formation. Minimum up and down time constraints, real power balance, real power operating limits of generating unit, start-up cost, and spinning reserve are all taken into account using ACSA. The paper presented test results on a 10-unit test system that proved effectiveness of ACSA in solving the UC problem. Derong Yu, et al. [50]proposed a hybrid algorithm to solve UCP depending on ant colony optimization (ACO) and Lambda-iteration method. A system of 10-60 was tested to solve UCP using the HACO algorithm results show HACO is more efficient and effective to implement the UCP. Nascimento, F.R et al.[51] used of Lagrange multipliers associated with discrete variables of the Thermal UCP as a source of information for the ant colony algorithm. It achieved by mitigating discrete variables, which are inherent to the problem through a sigmoid function. As a result, the non-linear optimization problem is solved by using the primal-dual interior-point method. Test results show that considering information improves the efficiency of the colony search process.

2.3. Unit commitment with wind energy

A modified unit commitment is proposed in[52]. It is updated on three periods (daily, quarter-hour and every minute). The effects of load and wind power change that could be forecasted before 24 hours is included. The quarter-hourly handles the fast continuous changing in wind power that predicted an hour ahead and commits peaking, regulation, and fast choosing economic units that could handle these changes in wind power. The minute updated unit commitment is used to connect or disconnect fast committed units or wind turbines based on a 15-minute forecasting of wind power variations with periods of time greater than 10 minutes. Methaprayoon, K , et al. [54]presents the Artificial Neural Network model for wind generation forecast and the approach to integrate the forecasted generation into unit commitment scheduling using probabilistic concept of confidence interval. The model has applied the computation of correlation coefficient to choose the best inputs. To improve the reliability of training,

data normalization has been exercised. The uncertainty of forecasting error is taken into account by utilizing the concept of confidence level. Therefore, the balance between the cost saving and the risk on system reliability because of committing based-load unit is handled. Hosseini, S.H, et al. [53] propose a method for unit commitment with high penetration of wind generation. Simulated annealing is used to deal with complex constraints of UC, which also activates reliability and emission constraints. A must run constraint was taken into account in this method. If any wind turbine goes off in UC, they must run constraint makes it on, and then calculates the reliability effect of committing wind farm on the generation system. The most expensive thermal units are decreased due to the new committed wind plants. Thus, wind farms that recommitted compensate 80 percent of the most expensive committed unit in that period.

Jianhui Wang, et al. [54] proposed a security-constrained unit commitment (SCUC) algorithm considering the volatility and intermittency of wind power generation. The unit commitment problem and the forecasted intermittent wind power generation are solved in the master problem. The next step is to simulate possible scenarios for representing the wind power volatility. In the subproblem, the initial dispatch is computed, and the redispatch is taken into account to satisfy the hourly volatility of wind power generation in simulated scenarios. It creates and adds Benders cuts to the master problem to revise the scheduling solution if the redispatch cannot mitigate violations. Numerical simulations show significantly the effectiveness of the presented algorithm to handle the security of power system operation by satisfying the intermittency and volatility of wind power generation. Constantinescu, E.M. et al. [55] presented a computational framework to integrate a state-of-the-art numerical weather prediction (NWP) model in stochastic UC/ED formulation considering wind power uncertainty. The NWP model is improved with an ensemble-based uncertainty quantification strategy. The paper discussed a computational problem that generates during the implementation of the framework and validates the model by taking real wind-speed from meteorological stations. The paper in [56] presented an analysis about how accommodate large part of wind power generation in power market operations using demand dispatch and the use of probabilistic wind power predicting. Dynamic operating reserve requirements were estimated by using probabilistic wind power forecasting, which based on the level of uncertainty in the forecast. In the case study, it was found that the efficient operation of electricity can be achieved by using the method of demand dispatch and probabilistic wind power forecasting.

3. Unit Commitment, Economic Dispatch and optimal power flow Formulation

3.1. Formulation of unit commitment

The objective of the UC problem as it was already defined is to minimize the total operating costs subjected to a set of system and unit constraints such as system power balance, system spinning reserve, and unit's minimum up and down times over the scheduling horizon. The production cost is a non-linear equation; however, it is approximated to express as a quadratic function which mathematically represented as:

3.1.1. The production cost

$$F(P_i) = a_i P_i^2 + b_i P_i + c_i \quad (1)$$

Where a_i , b_i , c_i are the coefficients of input-output characteristic of i th unit $F(P_i)$ represents the cost function and P_i is the power output.

3.1.2 Start-up and shut down costs

In addition to operating cost, there are a startup and shutdown costs should be included in UC problem. A certain amount of heat energy must be expended to bring a unit on-line due to the temperature and pressure of the thermal unit cannot move fast. This energy does not produce any MW generation from the unit and is included into the unit commitment problem as a start-up cost whose cost varies from a maximum "cold-start" value to a much smaller value depending on how far the boiler from operating

temperature. To treat a thermal unit throughout its down period, two approaches are used. The first approach leaves the boiler to cool down and heat back up to operating temperature in proper time for a scheduled turn on. The second (called banking) which certain amount of energy has to be supplied to the boiler to just maintain operating temperature. The two costs are as shown in Fig.1, and are compared while determining the UC schedule and a best approach among them is chosen.

$$\text{Start – up cost when cooling} = C_c \left(1 - e^{-t/\alpha}\right) F + C_f \quad (2)$$

Where: C_c is the cold-start cost (MBtu); F is fuel cost; C_f is a fixed cost (includes crew expense, maintenance expenses) (in \$); α is the thermal time constant for the unit; t is the time (h) the unit was cooled

$$\text{Start – up cost when banking} = C_t t F + C_f \quad (3)$$

Where C_t = cost (MBtu/h) of maintaining unit at operating temperature.

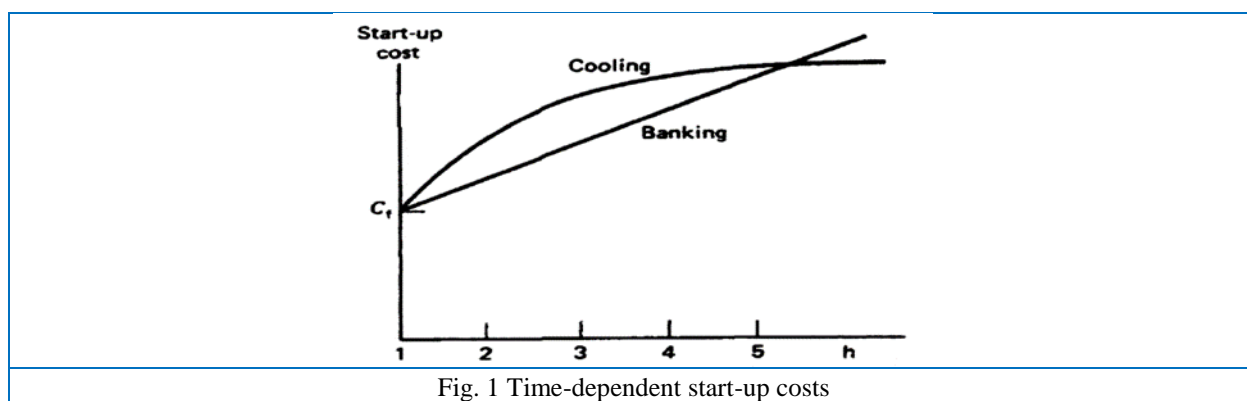


Fig. 1 Time-dependent start-up costs

Finally, the capacity limits of thermal units change frequently because of maintenance or unscheduled outages of various pieces of equipment in the plant; this should also be considered in unit commitment.

$$\text{Shud – down cost} = K P_t \text{ \$/h} \quad (4)$$

Where K is the incremental shutdown cost

3.1.3 Constraints

The unit commitment problems are subjected to many constraints that include:

3.1.3.1 Minimum up time:

Once a unit is online, it should not be turned off immediately.

$$T_i^{on}(t) \geq MUT_i \quad (5)$$

For $i = 1, 2, \dots, N.$

$t = 1, 2, \dots, T.$

3.1.3.2 Minimum down time:

Once the unit is OFF, there should be a minimum time before it can be put ON again.

$$T_i^{off}(t) \geq MDT_i \quad (6)$$

For $i = 1, 2, \dots, N.$

$t = 1, 2, \dots, T.$

3.1.3.3 Must Run

There are some units need to have must-run status during certain times of the year for some reasons such as voltage support on the transmission network or for such purposes as supply of steam for uses outside the steam plant itself.

3.1.3.4 Must out units:

Some units are set to must-out status for certain reasons like maintenance or forced outages. These units should not be taken into account during committing problem.

3.1.3.5 Fuel Constraints

Some units have limited fuel, or else have constraints that require them to burn a specified amount of fuel in a given time, presents a most challenging unit commitment problem.

3.1.3.6 Crew constraints:

The limitation of staffs in a plant that has more than one unit may limit the plant to run one unit at a time.

3.1.3.7 Power balance constraints

The generated power from all committed units must be equal to the load demand.

$$\sum_{i=1}^N P_{i,t} U_{i,t} = P_D \quad \text{for } t = 1, 2, 3 \dots \dots, T \quad (7)$$

3.1.3.8 Spinning Reserve

Spinning reserve is the term used to describe the total amount of generation available from all units synchronized (i.e., spinning) on the system, minus the present load and losses being supplied. Spinning reserve must be carried so that the loss of one or more units does not cause too far a drop in system frequency. Quite simply, if one unit is lost, there must be enough reserve on the other units to make up for the loss in a specified time period[10].

$$\sum_{i=1}^N P_{i,t} U_{i,t} \geq P_D + R_t \quad \text{for } t = 1, 2, 3 \dots \dots T \quad (8)$$

3.1.3.9. Ramp rate limits:

When units are in the start-up span, a pre-warming process should be introduced to prevent a brittle failure. Since the unit has physical limitations, the unit generating capability rises as a ramp function. Similarly, when a unit is in the shutdown process, it will take a while for the turbine to cool down. Before the unit generating capability decreases to its lower limit, the residual energy is to be used to meet the load demand, which is contrary to the case where the changes in unit generating capacity are modeled as a step function [4].

Ramp-rate limits for unit constrained generating capability.

$$c_i(t) - c_i(t - 1) \leq UR_i \quad \text{as unit } i \text{ starts up} \quad (9)$$

$$c_i(t - 1) - c_i(t) \leq DR_i \quad \text{as unit } i \text{ shuds down} \quad (10)$$

Ramp-rate limits for unit generation changes.

$$P_i(t) - P_i(t - 1) \leq UR_i \quad \text{as generation increases} \quad (11)$$

$$P_i(t - 1) - P_i(t) \leq DR_i \quad \text{as generation decreases} \quad (12)$$

3.1.3.10 Units minimum and maximum generation limit

Each unit has a minimum and maximum limit that cannot exceed.

$$P_{i,min} \leq P_{i,t} \leq P_{i,max} \quad \text{for } i = 1, 2, \dots, N \quad (13)$$

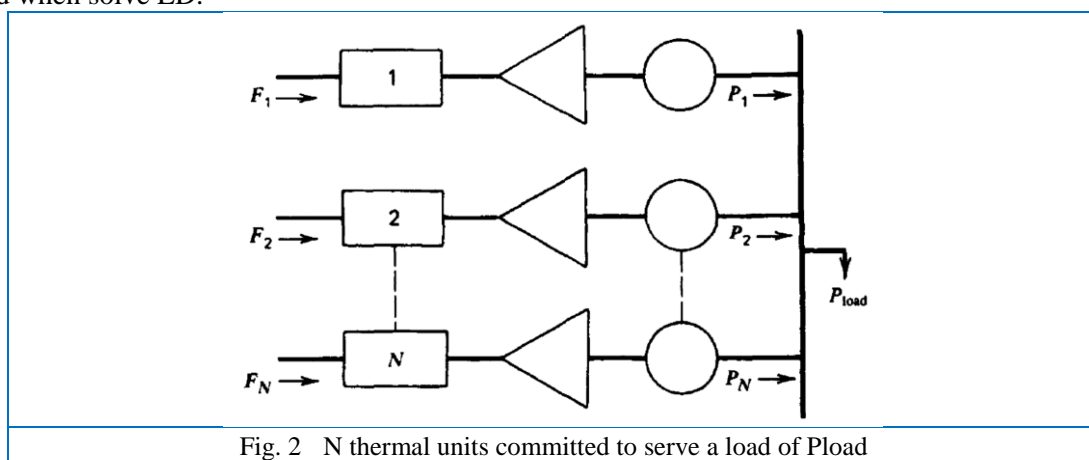
3.1.4 Objective function

$$\min C_{total} = \sum_{t=1}^T \sum_{i=1}^N F_i(P_{i,t})U_{i,t} + SU_i(1 - U_{i,t-1})U_{i,t} + SD_i(1 - U_{i,t})U_{i,t-1} \quad (14)$$

Where N is the number of thermal generating units; T is the number of considered time stage; $U_{i,t}$ is the status of unit i at stage t ; C_{total} is the total operating cost; $F_i(P_{i,t})$ is the fuel cost function of the i th unit; SU_i is startup cost; SD_i is the shutdown cost. The function(14) is subjected to the constraints: (5), (6), (7), (8), (13) and ramp rate limits.

3.2 Economic dispatch

Economic dispatch is a second phase in solving the unit commitment problem. UCP tries to minimize the total cost which includes both generation cost and start-up and shutdown costs of the units. The main job of economic dispatch is to minimize the cost of generation for a number of combinations after committing. The solution of ED problem is based on an equal incremental cost assumption. The criterion is that all units operate at equal incremental cost. It is simply obvious that the units have higher incremental cost contribute less output to the system, and the lower incremental cost units give more. Maximum and minimum limits, losses and security constraint are main constraints that should be satisfied when solve ED.



3.2.1 Objective Function:

$$F_{total} = F_1 + F_2 + \dots + F_N = \sum_{i=1}^N F_i(P_i) \quad (15)$$

Constrained by:

Unit generation limit:

$$P_{i,min} \leq P_i \leq P_{i,max} \quad \text{for } i = 1, 2, \dots, N \quad (16)$$

Power balance:

$$\sum_{i=1}^N P_i = P_D \quad \text{for } t = 1, 2, 3 \dots, T \quad (17)$$

The most popular method to solve ED is Lagrange multiplier, which optimizes a Lagrange function by converting the constrained problem into an unconstrained problem. The constraint function is included into objective function after multiplying with the Lagrange multiplier.

$$\mathcal{L}(P_i, \lambda) = F_t + (P_D - \sum_{i=1}^N P_i)\lambda \quad (18)$$

Where, λ is the Lagrange multiplier.

Obtaining the minimum by taking the partial derivative of the Lagrange function with respect to the power output values one at a time and makes it equal to zero.

$$\frac{\partial \mathcal{L}(P_i, \lambda)}{\partial P_i} = \frac{\partial F_t}{\partial P_i} - \lambda = 0 \quad (19)$$

$$\frac{\partial \mathcal{L}(P_i, \lambda)}{\partial \lambda} = P_D - \sum_{i=1}^N P_i = 0 \quad (20)$$

From equation (19)

$$\frac{\partial F_t}{\partial P_i} = \lambda \quad (21)$$

Form equation (15) and (21)

$$\frac{\partial F_t}{\partial P_i} = \frac{\partial \sum_{i=1}^N F_i(P_i)}{\partial P_i} = \lambda \quad (22)$$

$$\frac{dF_1(P_1)}{dP_1} = \frac{dF_2(P_2)}{dP_2} = \dots = \frac{dF_n(P_n)}{dP_n} = \lambda \quad (23)$$

The equation (23) shows that the optimal generation happens when the points at the slopes of input-output characteristics are equal as shown in Fig. So, the criterion to find the optimal output is that the incremental costs for all generators are the same.

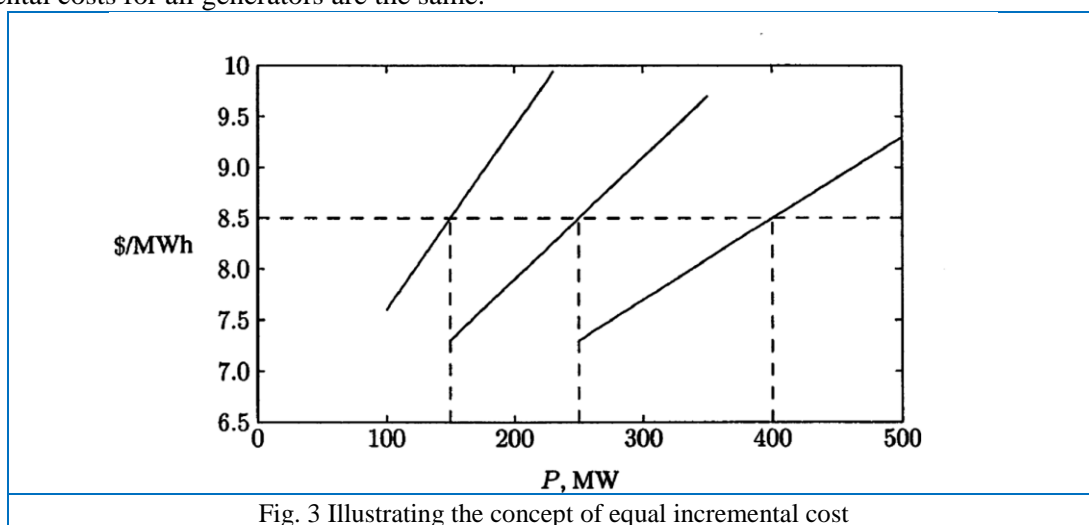


Fig. 3 Illustrating the concept of equal incremental cost

By taking the derivative of the cost function (3.1),

$$\frac{dF_i(P_i)}{dP_i} = 2a_i P_i + b_i = \lambda \quad (24)$$

Simplified to:

$$P_i = \frac{\lambda - b_i}{2a_i} \quad (25)$$

Now, λ can be found by using the equations (18) and (25)

$$\sum_i^N \frac{\lambda - b_i}{2a_i} = P_D \Rightarrow \lambda = \frac{\sum_{i=1}^N \frac{b_i}{2a_i} + P_D}{\sum_{i=1}^N \frac{1}{2a_i}} \quad (26)$$

The equation (26) helps to obtain the generation for each unit. But the formulation does not consider the minimum and maximum generation limits. A generating unit might exceed its minimum or maximum limits, which is not acceptable in solving ED. To solve this problem, any unit reaches its limit is fixed at that value and continue calculating the power generation for the remaining units based on equal incremental cost. Furthermore, the equations formulated above have not yet taken into account the impact of the transmission line losses and limits. This formulation is fit for committed units that are located at one plant as shown in Fig. . In reality, the power system is very huge, and it is located in very large areas. The most of its power plants are spread at far locations and interconnected with transmission lines to supply power, which leading to power losses. It is not practical to neglect the losses in the transmission lines. They should be included in the ED formulation to obtain realistic solutions. The transmission losses will be taken into account in the next formulation.

$$\sum_{i=1}^N P_i = P_D + P_{loss} \quad \text{for } t = 1, 2, 3 \dots \dots, T \quad (27)$$

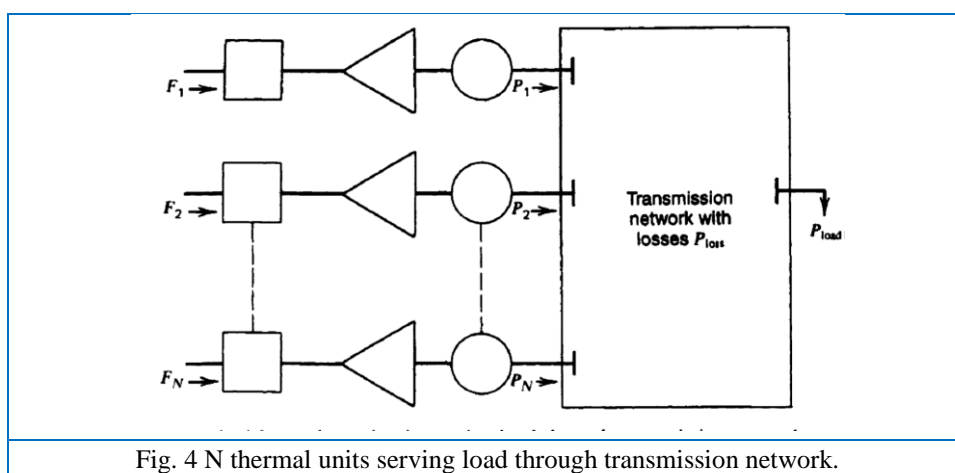


Fig. 4 N thermal units serving load through transmission network.

The loss in the transmission network, P_{loss} is a function of the network impedances and the currents flowing in the network. The currents will be considered only as a function of the independent variables P_i and the load P_D . There are N equations of this type to be satisfied along with the constraint equation shown in Eq. This collection, Eq. (25) plus Eq. (27), is known collectively as the coordination.

$$\mathcal{L}(P_i, \lambda) = F_t + \left(P_D + P_{loss} - \sum_{i=1}^N P_i \right) \lambda \quad (28)$$

Taking the derivative of the Lagrange function with respect to any one of the N values of p_i

$$\frac{\partial \mathcal{L}(P_i, \lambda)}{\partial P_i} = \frac{\partial F_t}{\partial P_i} - \lambda \left(1 - \frac{\partial P_{loss}}{\partial P_i} \right) = 0 \quad (29)$$

$$\frac{\partial F_t}{\partial P_i} = \lambda \left(1 - \frac{\partial P_{loss}}{\partial P_i} \right) \quad i = 1, 2, \dots, N \quad (30)$$

Taking the partial derivative with respect to λ .

$$\frac{\partial \mathcal{L}(P_i, \lambda)}{\partial \lambda} = P_D + P_{loss} - \sum_{i=1}^N P_i = 0 \quad (31)$$

From equation (28).

$$\lambda = \frac{\partial F_t}{\partial P_i} \left(\frac{1}{\left(1 - \frac{\partial P_{loss}}{\partial P_i} \right)} \right) \quad (32)$$

$$\lambda = \left(\frac{\partial F_t}{\partial P_i} \right) L_i \quad (33)$$

Where L_i is known as the penalty factor of plant I and is given by

$$L_i = \frac{1}{\left(1 - \frac{\partial P_{loss}}{\partial P_i} \right)} \quad (34)$$

The incremental transmission loss is obtained from the loss formula:

$$P_L = \sum_{i=1}^N \sum_{j=1}^N P_i B_{ij} P_j \quad (35)$$

Taking the derivative, yields.

$$\frac{\partial P_{loss}}{\partial P_i} = \sum_{j=1}^N 2B_{ij} P_j \quad (36)$$

Finally, P_i is found by gathering (23), (28) and (34) which yields.

$$P_i = \frac{\lambda \left(1 - \sum_{j=1, j \neq i}^N 2B_{ij} P_j \right) - b_i}{2(a_i + \lambda B_{ii})} \quad (37)$$

3.3 Optimal Power Flow

The optimal power flow (OPF) is one of the nonlinear constrained and occasionally combinatorial optimization problems of power systems. It was first discussed by Carpentier in 1962[57]. OPF had taken a lot of time until it became a successful algorithm that can be applied to the power system. The main objective of optimal power flow is to minimize the total production costs of the whole system to meet the load demand for a particular power system while keeping the security of the system operation. It is subjected to keep each device in the power system within its desired operation range at steady-state which include maximum and minimum outputs for generators, maximum MVA flows of power transmission lines and transformers, as well as system bus voltages within specified limits. OPF problem calculates optimal values of active and reactive power generations in addition to voltage magnitudes in a way that can minimize the power-generation cost [58]. The economic dispatch that was formulated above has one constraint ($P_{imin} \leq P_i \leq P_{imax}$) which hold the total generation to equal the total load with losses. OPF includes many more limits on power system, for example, bounds on reactive power generations ($Q_{imin} \leq Q_i \leq Q_{imax}$), transmission line flows, thermal limits, bus voltage magnitudes ($|V_{imin}| \leq |V_i| \leq |V_{imax}|$), and flows on transmission lines or transformers expressed in either MW, amperes or MVA ($MVA_{ijmin} \leq MVA_{ij} \leq MVA_{ijmax}$) These operating constraints make sure that the dispatch of generation does not force the transmission system into violating a limit, which may put it in danger of being damaged. The OPF may also consider the constraints that represent the

operation of the system after contingency outages, which allow the optimal power flow to dispatch the system in a defensive manner. The OPF is now forcing the system to be operated in a way that if any contingency happens, the resulting voltages and flows will still be within limits. Thus, constraints such as the following might be incorporated:

$$|V_i|^{min} \leq |V_i| \leq (\text{with line } ij \text{ out})|V_i|^{max} \quad (38)$$

$$MVA_{ij}^{min} \leq MVA_{ij} \leq (\text{with line } ij \text{ out})MVA_{ij}^{max} \quad (39)$$

This indicates that the OPF would prevent the post-contingency voltage on bus j or the post contingency flow on line $i j$ from exceeding their limits for an outage of line ij . This special type of OPF is called a “security-constrained OPF,” or SCOPF[10]. In the economic dispatch problem, the only adjustable variables were the generator MW outputs, whereas in the OPF, there are many more adjustable or “control” variables that may be specified. These variables include:

- ❖ Generator voltage.
- ❖ LTC transformer tap position.
- ❖ Phase shift transformer tap position.
- ❖ Switched capacitor settings.
- ❖ Reactive injection for a static VAR compensator.
- ❖ Load shedding.
- ❖ DC line flow.

Classical objective function:

Minimize total generating cost:

$$\min \sum_i^N C_i(P_i) \quad (40)$$

Minimize changes in the controls:

$$\min \sum_i^N C_i |u_i - u_i^0| \quad (41)$$

Subjected to:

Equality constraints:

Power balance at each node - power flow equations

$$P_k^g - P_k^D = \sum_{i=1}^N V_k V_i [G_{ki} \cos(\theta_k - \theta_i) + B_{ki} \sin(\theta_k - \theta_i)] \quad (42)$$

$$Q_k^g - Q_k^D = \sum_{i=1}^N V_k V_i [G_{ki} \sin(\theta_k - \theta_i) - B_{ki} \cos(\theta_k - \theta_i)] \quad k = 1, 2, \dots, N \quad (43)$$

Inequality constraints:

Limits on the control variables:

$$u^{min} \leq u \leq u^{max} \quad (44)$$

Operating limits on voltages

$$V^{min} \leq V \leq V^{max} \quad (45)$$

4. Implementation and Results

4.1 UC and ED implementation

Economic dispatch (ECDI) tool in PSS/E software is used to solve the unit commitment and find the power dispatch for each unit connected to the system. This tool uses the priority method to solve the UCP and lambda iteration to solve ED. The unit that has higher priority runs first, then followed by less priority according to power demand. Many factors play a role to select the priority list, for example, the incremental cost, emission cost, maintenance schedule, voltage support, etc. The solution obtained by PSS/E (ECID) tool does not take into account the losses in the system or constrain like ramp up and down, transmission line limitation, or voltage violation. These constraints and limitation will be considered in OPF solution. The PSS/E (ECDI) tool includes the equality constrain $\sum_i^n P_i = P_D$ and generation limit for each unit $P_{min} \leq P_i \leq P_{max}$

4.1.1 Data input

The representation of power networks in PSS/E consists of several categories of data of network and equipment elements; each data needs a particular type of data. The creation of a new case and data input for the IEEE 30-bus test system case is briefed in the steps below.

1. Create a new case from file>new.
2. Set the base MVA and frequency (100MVA, 60 Hz for all cases in this paper).
3. Input data for 30-bus using the spread sheet which include: Bus data, Machine parameter indicating their generation limits, Load table, fixed and switched shunt, branches indicating their rates (A, B, and C) , two and three transformers, etc.
4. In this step, economic dispatch data file is created (IEEE-30-bus.ecd). Data file includes all incremental heat rates, minimum and maximum generation limit, fuel price, and priority rank for each unit. The
- 5.
6. Table 1 and Fig. show the fuel cost and incremental heat rate for the six unit of the IEEE 30-bus system

Table 1 IEEE 30-bus data (*.ecd)

Bus #	ID	Priority	Fuel price	Gmax	Gmin	Heat min	Incremental heat curve points									
							0	1000	2000	3000	4000	5000	6000	7000	8000	9000
1	1	1	1	200	50	0	0	2000	40	2300	80	2600	120	2900	160	3200
2	1	1	1	80	20	0	0	1750	16	2310	32	2870	48	3430	64	3990
5	1	1	1	50	15	0	0	1000	10	2250	20	3500	30	4750	40	6000
8	1	1	1	30	10	0	0	3250	6	4250	12	5251	18	6252	24	7253
11	1	1	1	35	10	0	0	3000	8	3400	16	3800	24	4200	32	4600
13	1	1	1	40	12	0	0	3000	8	3400	16	3800	24	4200	32	4600

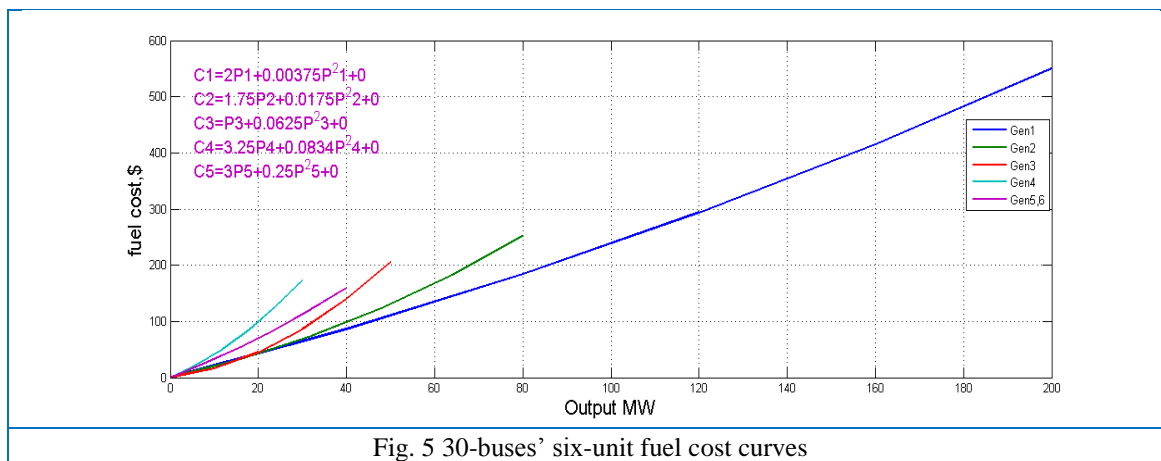


Fig. 5 30-buses' six-unit fuel cost curves

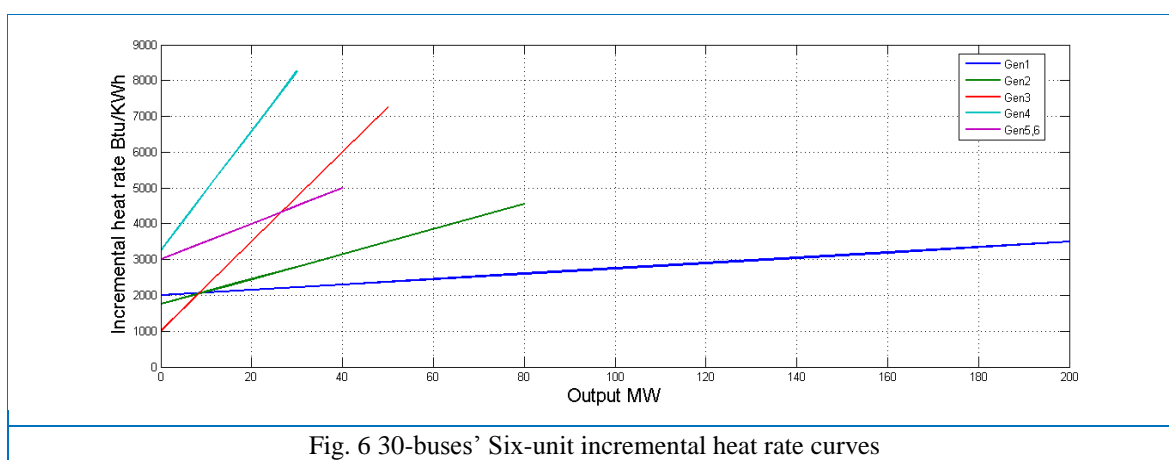


Fig. 6 30-buses' Six-unit incremental heat rate curves

4.1.2 Case 1: UC and ED for IEEE 30 bus test system using ECDI tool

The test performed for 24-hour period horizon with forecasting load shown in Fig. . The scheduling results and power shares for each unit are shown in Fig. 5. The results clearly have shown that ECDI tool did not consider the losses in the transmission system, nor constraints such as transmission line limits or voltage violation. The implementation started at load 186 MW putting unit one ON which has the cheapest fuel cost function. The unit 2 runs when the load exceeds the maximum limit of unit one. Hence, the units start to put online or offline according to the load demand and unit cost. However, the solution obtained by ECDI tool, as it uses the priority method, is not the optimal solution, and it is not realistic for a system whose units located in different locations. The tool is feasible for the units if they are all located in the same plant or location.

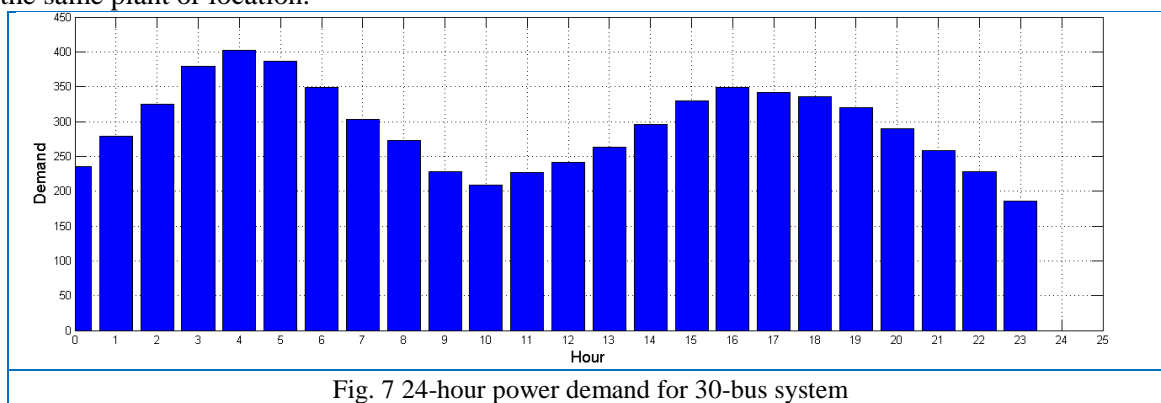


Fig. 7 24-hour power demand for 30-bus system

Table 2 Unit Commitment schedule for 30-bus system using ECDI tool

Hour	Load	Units						Output (MW)						Cost (\$)	Incremental cost
		1	2	3	4	5	6	1	2	3	4	5	6		
1	235	1	1	0	0	0	0	187.6	47.4	0	0	0	0	629	3.41
2	278	1	1	0	0	0	0	200	78	0	0	0	0	793	4.48
3	325	1	1	1	0	0	1	200	72.9	26	0	0	26	960	4.3
4	379	1	1	1	0	1	1	200	80	29.83	0	34.58	34.58	1154	4.73
5	402	1	1	1	0	1	1	200	80	47	0	35	40	1282	6.88
6	415	1	1	1	1	1	1	200	80	42	18	35	40	1335	6.25
7	410	1	1	1	1	1	1	200	80	39.14	15.85	35	40	1305	5.89
8	302	1	1	0	0	1	0	200	74.7	0	0	27	0	879	4.36
9	272	1	1	0	0	0	0	200	72	0	0	0	0	767	4.27
10	228	1	1	0	0	0	0	181.9	46.1	0	0	0	0	605	3.36
11	208	1	1	0	0	0	0	165.4	42.6	0	0	0	0	540	3.24
12	227	1	1	0	0	0	0	181	46	0	0	0	0	602	3.36
13	241	1	1	0	0	0	0	192.6	48.4	0	0	0	0	650	3.44
14	262	1	1	0	0	0	0	200	62	0	0	0	0	726	3.92
15	295	1	1	0	0	1	0	200	70.6	0	0	24.41	0	849	4.22
16	329	1	1	0	0	1	1	200	74.6	0	0	27	27	978	4.36
17	349	1	1	0	0	1	1	200	80	0	0	34	34	1068	4.73
18	342	1	1	0	0	1	1	200	80	0	0	31	31	1036	4.55
19	335	1	1	0	0	1	1	200	77	0	0	29	29	1004	4.45
20	319	1	1	0	0	1	1	200	70.4	0	0	24.3	24.3	935	4.21
21	289	1	1	0	0	1	0	200	67	0	0	22	0	824	4.1
22	258	1	1	0	0	0	0	200	58	0	0	0	0	710	3.78
23	228	1	1	0	0	0	0	181.9	46.1	0	0	0	0	606	3.36
24	186	1	0	0	0	0	0	186	0	0	0	0	0	502	3.4
Total cost													20739		

4.2 Optimal power flow

The solution obtained by the OPF tool in PSSE is more realistic and has many great advantages over the ECDI tool. The tool considers the losses in the power system, and it can include the generation reserve and ramp rate. The OPF tool has the ability to control most control variables in the power system to find the best power flow and economic dispatch without violating the system boundaries. The OPF tool can control phase shift angles, transformer tap ratios, switched shunt, and load adjustment. The OPF tool also is capable of monitoring system security like high or low voltage issues and branch or transformer overloads.

To perform OPF in PSSE, a new OPF data file must be created for the saved case. Then all data related to OPF should be entered. The points below indicate all data that is needed for IEEE 30-bus system.

Bus data, includes normal OPF maximum and minimum voltages, emergency OPF maximum and minimum voltages, limit type (hard, soft-linear limit, or soft-quadric limit), and soft limit penalty.

1. Adjustable bus shunt, includes initial, maximum and minimum susceptance in MVar and

- cost scale in \$ per MVar
2. Adjustable branch reactance, includes initial, maximum and minimum reactance multiplier and cost scale coefficient.
 3. Branch flow, includes line location and ID, maximum and minimum limits, maximum and minimum emergency limits, limit type (hard, soft-linear limit, or soft-quadric limit), and soft limit penalty.
 4. Adjustable bus load, which includes load location, load ID and load table.
 5. Adjustable load table, includes initial, maximum, and minimum load multiplier and cost scale.
 6. Generation dispatch, includes generator location and ID, the dispatch factor for the machine and dispatch table.
 7. Dispatch table, includes maximum and minimum generation, fuel price scale coefficient, cost curve type, and cost table.
 8. Generation reactive capability, includes machine location and ID, transient reactance, stator current limit, lagging and leading power factor, maximum reactive power generation and reactive capability limit (Enable, + Delta Efd inhibit, - Delta Efd inhibit, and Fixed Efd)
 9. Generation reserve, include bus number and ID, unit ramp rate, and unit capability.
 10. Objective functions should be entered for each unit through an OPF data table. Three types of function may be used in OPF: linear cost function, quadric cost function and polynomial cost function.

4.2.1 Solve OPF

After entering the data to the PSSE and before solving the OPF, the objective and the OPF settings should be specified first. There are many objectives in OPF tool, such as to minimize fuel cost, minimize active or reactive power losses, minimize adjustable branch reactance, and minimize adjustable bus loads. A user has to select the objectives according to particular case requirements. The objective of the OPF solution in this paper is to minimize the fuel cost. The OPF solution option includes control variables that could be manipulated to find the best OPF solution for a certain power case. The 30-bus was solved with hard limit type for voltages (which are between 1.05 and 0.95) and transmission lines. The hard limit option provides a strict binding to the system, preventing voltages and branch flow from exceeding their nominal values and limits. The soft limit option allows the voltages and branch flow to go beyond their nominal and limit values with imposing a penalty that increases with the increase of the violation size.

The tap ratio control has also been activated in solving these two cases. The results have indicated that tap ratio control has decreased the total system cost to a certain amount, but in reality, it has a small impact on the total cost. The tap ratio control can control the reactive power flow, so losses may be reduced. Besides, reducing reactive power flow through a transmission line, increases the active power flow, which leads to increase the transmission line's capacity.

The one-line diagram in Fig. illustrates the IEEE 30-bus OPF solved case. The diagram indicates the active and reactive power generation for each unit, and it also shows the power flow and percentage capacity for each transmission line. As shown from the diagram, the transmission line that connects bus 1 and bus 2 has reached its limit. This limitation enforces the system to supply a load from other more expensive units, eventually increasing the total operating cost.

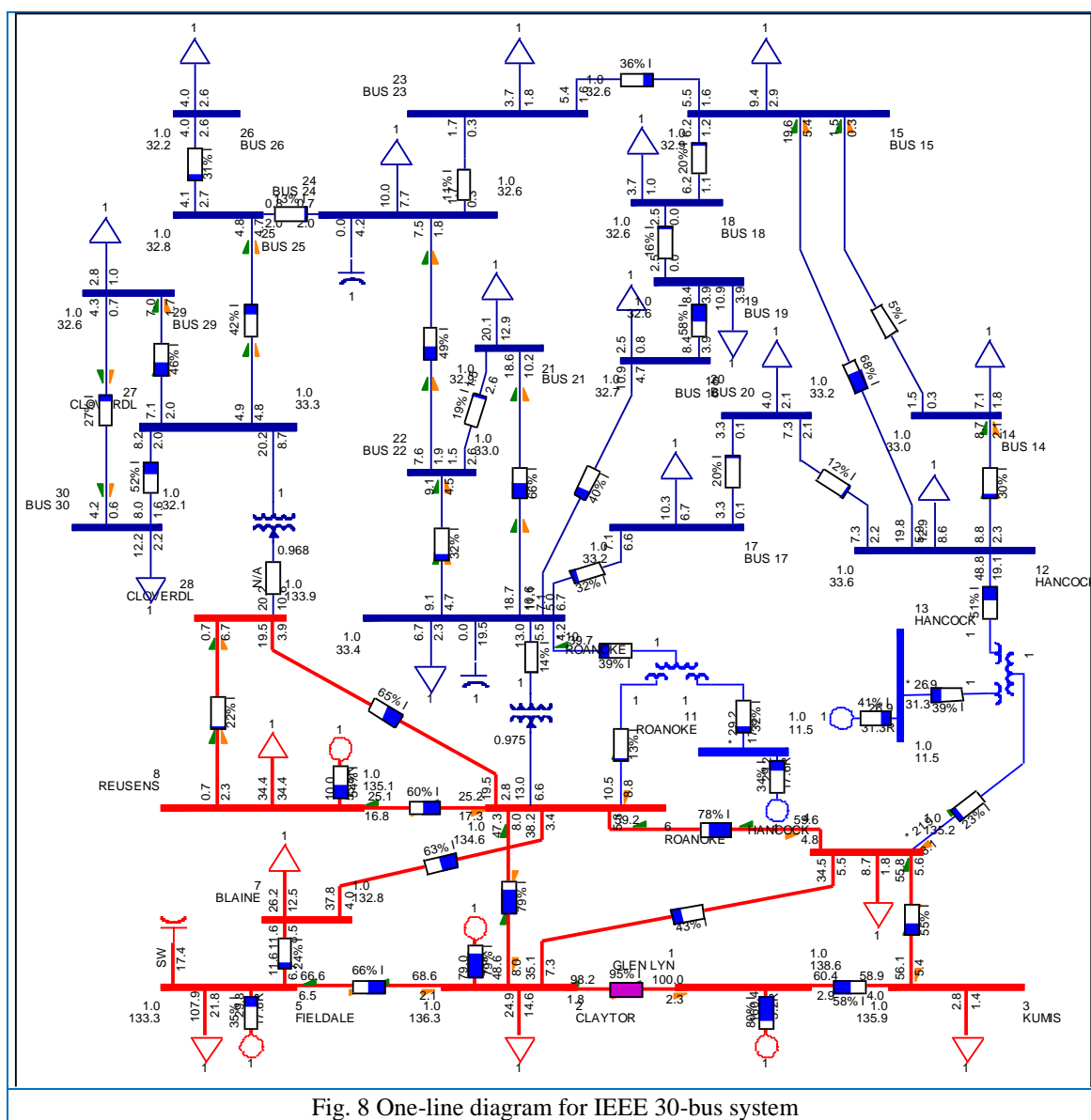


Fig. 8 One-line diagram for IEEE 30-bus system

4.2.2 Solving UC and ED using OPF tool

The OPF tool considers all constraints and limitations, and it also computes the losses in the power system. To find the optimal combination of units, the system is solved by the OPF tool with all units are in the service in the first step. In the second step, the units that reach its minimum value are turned off and solve the system again to find the economic dispatch for each unit. The units' schedule, economic dispatch, and the losses are shown in the Table 3. However, the system with the loads 402, 405, and 410 MW cannot be solved due to transmission line limitation. To solve this problem, the transmission line constraint option has to be changed from hard to soft type limit. This option allows transmission lines to carry more than their limits, but with applying a penalty increases with the increase of MWs that go beyond the specified limits.

Table 3 Unit Commitment schedule for 30-bus system using OPF tool

Hour	Load	Units schedule						Output (MW)						Cost (\$)	Losses (MW)
		1	2	3	4	5	6	1	2	3	4	5	6		
1	235	1	1	1	0	0	1	154.85	45.25	20.11	0	10.20	12.05	633	7.46
2	278	1	1	1	0	1	1	158.47	64.05	25.38	0	20.41	18.71	797	9.02
3	325	1	1	1	1	1	1	160.37	79.04	29.76	10	29.14	26.9	998	10.21
4	379	1	1	1	1	1	1	159.49	80	50	30	30	40	1319	10.49
5	402	1	1	1	0	1	1	200	80	46.27	20.6	30	40	1357	14.87
6	405	1	1	1	1	1	1	200	80	48	22	30	40	1378	15
7	410	1	1	1	1	1	1	200	80	50	25	30	40	1415	15
8	302	1	1	1	0	1	1	159.75	73.82	28.17	0	26.21	24.02	900	9.97
9	272	1	1	1	0	1	1	158.13	61.62	24.70	0	18.97	17.40	773	8.82
10	228	1	1	1	0	1	0	160.62	44.96	20.07	0	10.24	0	610	7.89
11	208	1	1	1	0	1	0	144.54	41.03	18.76	0	10.05	0	542	6.38
12	227	1	1	1	0	0	1	158.36	44.41	19.9	0	0	12.05	607	7.72
13	241	1	1	1	0	1	1	161.37	45.15	20.19	0	10.25	12.06	653	8.02
14	262	1	1	1	0	1	1	176.44	48.86	21.45	0	12.53	12.28	729	9.56
15	295	1	1	1	0	1	1	197.21	54.14	23.29	0	16.74	15.7	854	12.08
16	329	1	1	1	1	1	1	160.39	79.89	30.63	10.03	29.85	28.57	1017	10.36
17	349	1	1	1	1	1	1	159.54	79.99	37.63	12.58	29.99	39.91	1119	10.64
18	342	1	1	1	1	1	1	159.77	79.98	34.99	10.92	29.98	36.91	1081	10.55
19	335	1	1	1	1	1	1	160.15	79.97	32.71	10.09	29.97	32.59	1046	10.48
20	319	1	1	1	1	1	1	160.08	76.66	29.01	10.02	27.76	25.51	971	10.04
21	289	1	1	1	0	1	1	159.06	68.53	26.66	0	23.07	21.14	842	9.46
22	258	1	1	1	0	1	1	157.35	55.92	23.09	0	15.6	14.36	717	8.32
23	228	1	1	1	0	1	0	156.40	47.60	20.73	0	10.97	0	610	7.7
24	186	1	1	1	0	0	0	134.93	38.74	17.98	0	0	0	470	5.64
Total cost													21438		

6.3 Solving UC, ED and OPF with wind power penetration

At this stage, the UC, ED, and OPF have been solved for the IEEE 30-bus system by including wind power generation. The solution is based on the wind power forecasting for 24 hours that shown in Fig. . A wind power farm of 100 MW rated power was added to the 30-bus system which has almost zero operating cost. The plant is connected to bus 8 to supply a load as much as it can without violating the transmission line limit. However, if the plant was connected, for example, to bus 1, 2 or 3, it would not supply all power that it produces due to the transmission line limit in this area. For example, the plant supplies only 44 MW, even though it can generate 84 MW. The OPF tool has been used to solve the UC and ED with including all system constrains and security criteria.

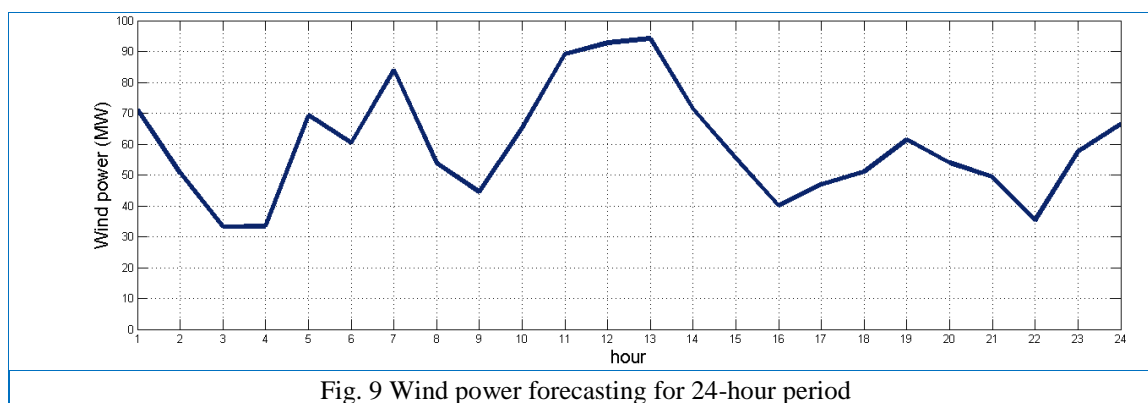


Fig. 9 Wind power forecasting for 24-hour period

The unit schedule and power share for each unit are shown in Table 4. As it is noticeable the wind plant supplies all possible power generated. In other words, the transmission lines are capable of carrying any power generated by a wind plant for any value of load during a day. The total operating cost has been minimized to 16861\$

Table 4 UC and UD for 30-bus system with wind penetration

Hour	Load	Units schedule							Output (MW)						W	Cost (\$)
		1	2	3	4	5	6	7	1	2	3	4	5	6		
1	235	1	1	0	0	0	0	1	132.24	38.24	0	0	0	0	71	443
2	278	1	1	1	0	1	0	1	156.71	56.52	23.35	0	0	0	50	632
3	325	1	1	1	0	1	1	1	157.81	70.62	27.39	0	23.86	21.99	33	867
4	379	1	1	1	1	1	1	1	157.57	79.99	37.54	12.04	29.99	39.84	33	1118
5	402	1	1	1	1	1	1	1	156.16	79.99	38.56	0	29.99	39.92	69	1080
6	405	1	1	1	1	1	1	1	156.01	79.99	38.44	12.22	29.99	39.92	60	1128
7	410	1	1	1	0	1	1	1	155.39	79.99	35.8	0	29.98	36.86	84	1051
8	302	1	1	1	0	1	0	1	156.41	59.79	24.34	0	17.42	0	53	708
9	272	1	1	1	0	0	0	1	157	56.23	23.24	0	0	0	44	630
10	228	1	1	0	0	0	0	1	131.24	37.98	0	0	0	0	65	438
11	208	1	1	0	0	0	0	1	94.22	29.13	0	0	0	0	89	314
12	227	1	1	0	0	0	0	1	107.92	32.41	0	0	0	0	92	607
13	241	1	1	0	0	0	0	1	118.25	34.9	0	0	0	0	94	399
14	262	1	1	1	0	0	0	1	139.27	39.92	18.65	0	0	0	71	510
15	295	1	1	1	0	1	0	1	155.35	55.39	23.1	0	14.78	0	55	674
16	329	1	1	1	0	1	1	1	157.27	69.66	27.15	0	23.2	21.4	40	858
17	349	1	1	1	0	1	1	1	157.75	75.55	28.88	0	26.6	24.55	46	921
18	342	1	1	1	0	1	1	1	156.91	71.25	27.66	0	24	22.17	50	875
19	335	1	1	1	0	1	1	1	155.29	64.37	25.74	0	19.8	18.36	61	804
20	319	1	1	1	0	1	1	1	155.24	60.82	25.64	0	17.81	16.52	53	768
21	289	1	1	1	0	0	0	1	158.83	64.76	25.64	0	0	0	49	680
22	258	1	1	1	0	0	0	1	156.54	52.38	22.14	0	0	0	35	607
23	228	1	1	1	0	0	0	1	122.97	35.92	17.28	0	0	0	57	441
24	186	1	1	0	0	0	0	1	94.52	29.16	0	0	0	0	66	308
Total cost															16861	

The OPF solution for the 30-bus system is illustrated in Fig. 10 and the report in Table 4. The solution is included all system constraints such line limit, voltage security, and unit limit. The system solved also with 10 percent generating reserve to overcome wind prediction error, load forecasting error, or any contingencies may happen.

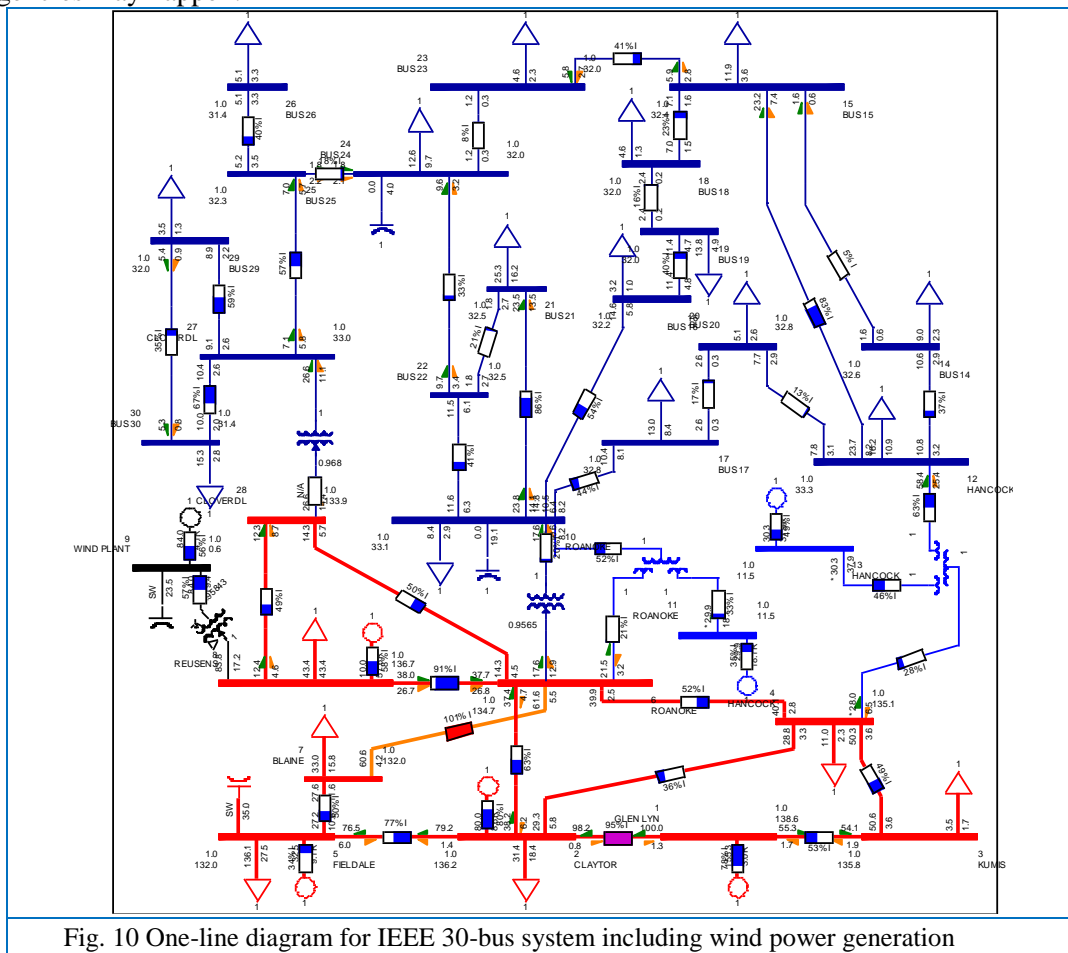


Fig. 10 One-line diagram for IEEE 30-bus system including wind power generation

5. Conclusion

Unit commitment is the crucial application in the daily operational planning of the power system, and it is one of the methods that power system operators depend on to minimize the total operation cost. UC is a complex combinatorial optimization problem that needs to be solved by taking all equality and inequality constraints in the power system. Economic dispatch is the second subproblem that deals with finding the optimal power output from each unit after solving the unit commitment problem. The optimal power flow is the broader problem that considers the whole system constraints. It solves power system without violating system standard and limitations. Intermittent and forecasting errors of wind should be taken into account when solving unit commitment and economic dispatch.

In this paper, formulation of unit commitment, economic dispatch, and optimal power flow problems and constraints related to them have been explained. PSSE software is used to solve UC, ED and OPF with including a significant amount of wind generation. A power system IEEE 30-bus has been studied as test system. The optimal combination of units was found by using ECDI and OPF tools. ECDI utilizes the priority list concept to find the best units' schedule, but it does not consider system losses and constrains. While the OPF tool solution is more accurate and reliable in solving UC and ED. The UC, ED, and OPF solutions included constrains like generation reserve, which it is very important to overcome load and wind forecasting errors and contingencies, ramp rates, unit generation limit, transmission line limit, and voltage security.

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