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#### A REVIEW OF RECENT ADVANCES IN ECONOMIC DISPATCH

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#### ABSTRACT

This paper presents a survey of papers and reports which address various aspects of economic dispatch. The time period considered is 1977-88. This is done to avoid any repetition of previous studies which were published prior to 1977. Four very important and related areas of economic dispatch are identified and papers published in the general area of economic dispatch are classified into these. These areas are:- (i) Optimal power flow, (ii) economic dispatch in relation to AGC, (iii) dynamic dispatch and (iv) economic dispatch with non-conventional generation sources.

Keywords:Economic dispatch, Literature review, Improved methodologies, Automatic generation control, Security constrained dispatch, Dynamic dispatch, Non-conventional generation sources.

#### INTRODUCTION

Economic dispatch is defined as the process of allocating generation levels to the generating units in the mix, so that the system load may be supplied entirely and most economically. A general survey of the present status of economic dispatch is done in this paper. The papers and reports reviewed here have been published subsequent to the comprehensive surveys done by Happ [1] and an IEEE Working Group [2,3]. Both Happ raviews the progress of optimal dispatch going as fa back as the early 1920's, when engineers were concerned with the problem of economic allocation of generation or the proper division of the load among the generating units available. Prior to 1930, various methods were in use such as: (a) the base load method where the next most efficient unit is loaded to its maximum capability, then the second most efficient unit is loaded to its maximum down to the least efficient unit, etc. It was recognized as early as 1930, that the incremental method, later known as the equal incremental method, yielded the most economic results. The theoretical work on optimal dispatch later ide to the development of analog computers for properly executing the coordination equations in a dispatching environment. A transmission loss penalty factor computer was developed in 1954 and was used by AEP in conjunction with an incremental loading slide rule for producing daily generation schedules in a load dispatching office. An electronic differential analyzer was developed for use in economic scheduling for off-line or on-line use by 1955. The use of digital computers for obtaining loading schedules was investigated in 1954 and was used by AEP in conjunction with an incremental load ing slide rule for producing daily generation schedules in a load dispatching office. An electronic differential analyzer was developed for use in economic scheduling for off-line or on-line use by 1955. The use of digital computers for obtaining loading schedules was investigated in 1954 and is used to this day.

Generation dispatch has been widely studied and reported by several authors in books on power system analysis [4,5,6,7,8,9,10,11,12,13,14,15,16]. Some authors present various aspects of optimal power flow while others present the development of interfaces between such control actions such as economic dispatch (ED) and load frequency control (LFC). Economic dispatch and load frequency control both have the task of adjusting the area generation

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such that it matches the area load while, simultaneously, both area frequency and the net tie-line exchange are at their set points. Even though ED and LFC have different time horizons, they are not independent. Because ED provides the set point for LFC. Now both of these control actions fall under a single activity called "Automatic Generation Control (AGC)". But this was not the case in the early years. Traditionally, there was minimal interface between area control (economic dispatch plus load frequency control) and local unit control. With modern equipment now available for generation, AGC has been improved considerably. This fact will be evident from our bibliographic search.

Two recent papers [17,18] published in the IEEE proceedings also stress on economic dispatch in the perspective of other control functions within a control center.

Finally, a three part series by the IEEE Working Group 71-2, on Operating Economics lists papers on economy-security functions published between the years 1959 and 1972 [2] and between the years 1973 and 1979 [3].

The contribution of our paper is, therefore, in the presentation and discussion of papers published in the years 1977 through 1988. Four very important and related areas of economic dispatch are identified and papers published in the general area of economic dispatch are classified under one of these four categories. The categories are:

- Optimal power flow.
- Economic dispatch in relation to AGC.
- Dynamic dispatch.
- Economic dispatch with non-conventional generation sources.

### **OPTIMAL POWER FLOW**

The optimal power flow procedure consists of methods of utilizing load flow techniques for the purpose of economic dispatch. While some authors have used the ac load flow model others have used the dc load flow model. The latter is based on the P-Q decomposition and then using known optimization techniques. The ac optimal load flow problem on the other hand consists of finding the active and reactive power output and the voltage magnitudes at any generator unit, in order to minimize the operating cost while meeting various security constraints. Security constrained dispatch involves those dispatch activities which are constrained to respect selected system security limits. In general, optimal power flow requires use of network modeling as well as resource modeling and naturally results in higher system costs.

The techniques used in solving optimal power flow as reported in the literature range from improved mathematical techniques to more efficient problem formulation. Among the mathematical techniques, some of the more important ones are the following:

- i) transportation method;
- ii) successive minimum cost flow technique;
- iii) reduced Hessian-based optimization technique;
- iv) modern mathematical optimization methods such as sequential, quadratic, linear, non-linear, integer and dynamic programming techniques;
- v) constraint relaxation; and
- vi) network approach.

Carpentier [19] chronicles the development of optimal power flows from its inception in 1961 and goes on to review several solution methods in existence in 1978. The author categorizes the methods into three families:-

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- Classical economic dispatch.
- General static optimization non-compact methods.
- General static optimization compact methods.

Classical economic dispatch is limited to real power optimization, taking losses into account, but without security. The non-compact methods include the injections method, the Hessian approach, the Dommel-Timney reduced gradient method and the generalized reduced gradient method. The compact methods reviewed are linear and non-linear optimization methods which use several different algorithms.

A review of the optimal power flow (OPF) methods is also provided by Talukdar, et al. [20] and Burchett, et al. [21]. The authors in both of these references discuss the relative performance criteria for different methodologies being employed in these procedures.

Several authors have presented more efficient algorithms in the application of linear and non-linear programming methods. Megahed, et al. [22] propose the conversion of the nonlinearly constrained dispatch problem to a series of constrained linear programming problems. System voltages, active and reactive generation, and the phase angles are considered as part of the OPF problem. These quantities are used in the loss formula. According to the authors, the method is fast and has good convergence characteristics.

Stefani, et al. [23] introduce a two-level optimization method for optimal power flow. The first level problem consists of the minimization of certain performance indices subject to a number of local constraints and power balance equation. The second level is the search for a global optimum obtained by choosing on the supremal level, the values of proper coordinating variables.

Irving, et al. [24] use a dual revised simplex algorithm for economic dispatch. A highly sparse factorization of the basis matrix is maintained during execution of the algorithm. In case of feasible solutions, the constraints are relaxed so as to reach a feasible solution.

Luo, et al. [25] reduce the economic dispatch problem to a concise set of quasi-linear equations resulting in a solution form similar to that of an electric network. The equations are in terms of the bus incremental cost, otherwise known as the Lagrange multipliers.

Luo, et al. [26] using ideas from their previous paper [25] develop a network model for the economic dispatch problem using the bus incremental costs as potential quantities. According to the authors' theory, an area system may be reduced to a Thevenin equivalent for economic dispatching by means of the network model.

Mota-Palomino, et al. [27] use a linearized formulation of the general optimal load flow problem and apply minimization technique to an augmented cost function which contains a piecewise differentiable penalty cost function term.

Lugtu [28] introduces the combined use of the differential algorithm and the simplex procedure of optimization in the security constrained dispatch. The constraints considered by the author are generation operating limits and response constraints, transmission constraints and system reserve constraints. According to the authors, significant storage reductions are achieved owing to the tableau sparsity, compared to the Dantzig-Wolfe algorithm or quadratic programming to security dispatch is presented by Stott, et al [29]. The authors apply the revised simplex method to the primal problem, using dual, reduced basis and relaxation techniques. The process starts from an initial power system operating stage containing branch overloads. Violated branch-flow limits are enforced one by one, optimally rescheduling the system on each occasion and testing for

Elacqua, et al. [30] present the results of using the method devised in reference [28] to a large power system. The authors report successful implementation and operation of the method.

Waight, et al. [31] have used the Dantzig-Wolfe decomposition method to resolve the economic dispatch problem into a master problem and several smaller linear programming subproblems. The algorithm that they have followed is as follows:

- · Decompose the problem into n subproblems and a master
- Chose the initial basis of the master problem by introducing artificial variables and setting up the appropriate Phase I (feasibility) and Phase II (optimality) objective functions.

- Compute an objective function for each subproblem and solve each subproblem using the revised simplex method.
- Calculate the relative cost factors for all subproblems. If all are positive, stop since optimality has been reached. Otherwise, reiterate with new simplex multipliers.

Somuah, et al. [32] reformulate the economic dispatch problem by introducing an added constraint on maximum frequency deviation following a postulated disturbance. The main difference between the frequency deviation constrained dispatch and the conventional economic dispatch is the allocation of the total system margin. In the latter case, the margin allocation is made without explicit consideration of the minimum frequency following a specified disturbance. The method of solution adopted by the authors is a Dantzig-Wolfe decomposition technique followed by several linear programming solutions. An algebraic formula is developed for the maximum frequency deviation.

Romano, et al. [33] apply the Dantzig-Wolfe decomposition principle to the OPF problem. This reduces the dimension of the problem into several subproblems which correspond to physical areas that can be identified in the power network. The optimization routine is based on the revised simplex method in association with a fast decoupled load flow method.

Shoults, et al. [34] present an alternative approach for computation of loss coefficients, or more popularly known as B-Constants. The authors have used the method of least squares to this end and have demonstrated the simplicity and computational advantages over methods based on the earlier Kror's method. The method used a linear relationship between real and reactive power outputs of a generator as well as an optimally ordered ---factorization method for direct solution, thus avoiding the formation of Z-bus explicitly. The authors incorporate this method of computing loss coefficients in a classical economic dispatch and demonstrate its computational advantage over a dispatch method using load flow techniques.

El-Hawary, et al. [35] study the relative performance of four algorithms used for parameter estimation in models used for optimal power flow. The models are 1) weighted least squares, 2) Gauss-Newton method or Bard algorithm, 3) Marquardt algorithm, and 4) Powell regression algorithm. The authors found an overall better performance by the weighted least squares method. In another paper of a similar nature, El-Hawary, et al. [36] compare the performance of a hybrid method of Powell and the Newton-Raphson method. Faster solution of the coordination equations are achieved by the former method thus making its convergence characteristics superior.

A method which combines linear programming with the Newton approach for solving optimal power flows is described by Maria et al. [37]. A decidedly faster solution results. Kirchen, et al. [38] use linear programming techniques in their solution of the OPF but with the additional capability of rescheduling the active power control to make corrections for voltage magnitude problems. The authors contend that no additional computing time would be required when the corrections are achieved by reactive means.

Several authors have used real-reactive decompositions of the optimal power flow.

Lee, et al. [39] introduce a method based on three separate modules but coupled to one another. The first one called the P-optimization module, which is equivalent to the conventional economic load dispatch, optimally allocates the real power generation among generators. The second module, called the Q-optimization module, optimally determines the reactive power output of generators and other various sources, as well as transformer tap settings. Finally the load flow module makes fine adjustments on the results of P and Q-optimization modules. The optimization problem is solved by the use of the gradient projection method.

Guoyu, et al. [40] present the concept of participation factor load flow, as a means of modeling the closed loop real power dispatch. In the authors' formulation, the real generation set points and the participation factors are specified for all system generators, instead of all real generations except the slack bus. The corresponding economic dispatch strategy is based on a decoupled scheme consisting of two stages of real and reactive power dispatch.

Shoults, et al. [41] formulate the optimal power flow problem as a decoupled P-Q optimization problem. The P-problem is the minimization of hourly production costs through control of generator real power outputs. The Q-problem is the minimization of real power transmission losses through control of generator terminal voltages,

transformer tap-settings and shunt capacitor/reactors. The non-linear optimization technique called the first order gradient method is applied to each subproblem.

Lee, et al. [42] combine the P- and Q-optimization procedure with a load flow in their solution of the OPF problem. The authors apply the gradient projection method to solve the P and Q subproblems and the Newton-Raphson method for the load flow.

Many authors have used non-linear optimization techniques for solving the OPF problems.

Aoki, et al. [43] present a new method to solve an economic load dispatch problem with dc load flow type network security constraints. The network security constraints represent the branch flow limits on the normal network and the network with circuit outages. Hence, the problem contains a large number of linear constraints. In power systems, only a small number of flow limits may become active. Computationally, since it is inefficient to deal with such constraints simultaneously, the authors have extended the quadratic programming technique into the parametric quadratic programming method using the relaxation method. The memory requirements and execution times suggest that the method is practical for real-time applications.

Contaxis, et al. [44] formulate the optimal power flow problem as a non-linearly constrained optimization problem recognizing system losses, operating limits on the generation units and line security limits. The OPF problem is decomposed into real and reactive subproblems and the two subproblems are solved alternately, by a transformation into quadratic programming problems through the use of the Generalized Generation Distribution Factors.

Pereira, et al. [45] describe a method for the solution of the security-constrained dispatch that can take into account the system rescheduling capabilities. The methodology is based on the Bender's Decomposition principle which allows the iterative solution of a base-case economic dispatch and separate contingency analysis with generation rescheduling.

Wood [46] proposes a new methodology to incorporate reserve constraints. He shows a technical solution to the reserve constrained problem which can be achieved with a very efficient use of computer resources. The problem is expressed as a dynamic programming scheduling problem and a feasible, but suboptimal solution is proposed which eliminates the usual search space problem. This method reduces the problem to a backward sequence of dispatch problems, with the generator limits being carefully adjusted between each time interval in the solution sequence.

Bosch [47] presents a solution to the optimal power flow problem constrained by reserve and power rate limits. The solution is obtained with a special projection having conjugate search directions that quickly and accurately solves the associated non-linear programming problem with up to 9600 constraints. The author proves that the proposed methodology reduces fuel costs by about 0.5%.

In a series of papers, Burchett, et al. [48],[49],[50] have reported the formulation and implementation of several methods of solving the OPF problem. These methods range from Quasi-Newton approach to sequential quadratic programming. In [48], the authors apply an optimization method based on transforming the original problem to that of solving a sequence of linearly constrained subproblems using an augmented Lagrangian type objective function. The subproblems are optimized using any one of the descent directions which include quasi-Newton, conjugate directions and steepest-descent. The algorithm has been successfully tested on a 500 bus system.

Burchett, et al. report in reference [49], the use of an optimization technique on a sequence of non-linear subproblems which are linearity constrained. A Quasi-Newton descent direction is used for optimizing the subproblems and the non-linear constraints are linearized by using the Newton-Raphson Jacobian matrix. Another new method is described by Burchett et al. in reference [50]. In this method, a sequence of quadratic programs are created from the exact analytical first and second derivatives of the power flow equations and the non-linear objective function. A sequential quadratic programming is then used to solve the problem. According to test results provided by the authors, this method gives the best performance in terms of computation time.

Merritt, et al. [51] apply the security constrained optimization technique reported in [49] and [50] to a case study of the New York

power pool bulk transmission system. The study is concerned with the determination of the amount, loaction and type of high voltage capacitors. Comparison of results with those of a conventional power flow study indicate several advantages of using the authors' OPF solution techniques.

Palmer et al. [52] address the problem of determining the reactive scheduling on an hourly basis. The power flow equations are linearized for each specified contingency case and a sequential linear programming method is used to determine capacitor schedules while enforcing all voltage limits. The multi-contingency optimization model is assigned to replace the hundreds of power flow solutions required by a conventional approach. As an extension of the preceding work, El-Kady, et al. [53] report results of a study which assesses possible savings in active transmission losses from using an optimal power flow program to schedule the generator voltages and transformer taps. The authors use a sequential direct quadratic programming technique. According to the authors, execution times using this method compared with a quasi-Newton algorithm suggest its applicability to real-time implementation.

Bacher, et al. [54] describe a method for solving the OPF in real time. The authors break the problem into two stages. The first stage is a full OPF based on linear programming technique and relying on the State Estimator solution as a base case and reschedules generation in the event of branch overloads. The authors refer to this stage as Security Dispatch. In the second stage referred to as Constrained Economic Dispatch, piecewise quadratic cost curves are used and quadratic programming is applied for the optimization. Only the second stage is used in real-time mode which is claimed to be as fast as classical economic dispatch.

Outside of the linear and non-linear programming based methods, other authors have either introduced newer techniques or improved pre-existing algorithms. Since 1982, Talukdar, Giras and Kalyan have collaborated on applying the Han-Powell algorithms to the solution of OPF [55,56,57]. The authors apply a dimension reduction procedure of the specific algorithm. Techniques such as network dissection and parallel processing are used for the objective.

Lee, et al. [58] describe the application of the Minty algorithm to economic dispatch. Since this algorithm requires a set of starting power flow conditions which satisfy the law of conservation of power at each node, the authors chose to use the Fulkerson minimum cost flow method formulated in a linear form. The Minty algorithm uses a stepwise approximation of the generator and transmission line incremental costs to find the optimum. The method gives comparable results to those obtained from another method using penalty factors and is claimed to be faster than the latter. In another paper published at a later date, Lee, et al. [59] present an improved method compared to their previously described method using the Minty algorithm. Their method consists of successive application of the dintry and low level transportation method, the authors use a modified version of the first level of optimization. This results in significant reduction in required computer time.

Bottero, et al. [60] formulate the reduced Hessian with respect to the m controllable real generations, as part of an iterative economic dispatch scheme without resorting to penalty functions. It is shown that in the solution algorithm, the m by m Hessian can be explicitly computed as a full matrix needing just 2m + 1 parameters to describe rather than  $m^2$ . The inverse of the matrix also requires 2m + 1 parameters, thus permitting the efficient use of a low storage Hessian-based search technique.

Another algorithm requiring less storage because of reduction in the size of the equality constraint model is introduced by Roy, et al. [61]. The authors use a cartesian coordinate formulation for the constraints. The voltage and power at each bus is classified as parametric and functional inequality constraints and are handled by reduced gradient technique and penalty factor approach respectively. The algorithm has proved to be three to four times faster than the Dommel-Tinney algorithm, a widely used optimal power flow algorithm.

Lin, et al. [62] formulate the economic dispatch problem with multiple intersecting quadratic cost functions and use a hierarchical structure to represent the power system. Vojdani, et al. [63, 64] and Huneault, et al. [65] apply the continuation method to optimal power flow. This method provides optimum trajectories of the system variables as a function of the varying parameter which can be system load, generation limits, transmission limits, etc. The authors claim that the continuation method proves very reliable and is particularly useful when other methods fail to achieve convergence. Reinstein et al. [66] provide results of using the continuation method to the IEEE reliability test system. They simulate the OPF problem under transmission and generation constraints.

Chandrashekhar, et al. [67] present a method for dynamic security dispatch which systematically satisfies all major requirements in the selection of an operating point. The authors augment the usual cost function to include a measure of transient stability across selected cutsets of faults. The optimization algorithm then effects a trade-off between optimal economy and steady-state and dynamic security. Chandrashekhar [68] presents a modified algorithm of that introduced in reference [67] for the dynamic security constrained dispatch. To better suit an on-line environment, the author has reformulated the optimization problem.

Lin, et al. [69] present a real time economic dispatch method by calculating the penalty factors from a base case data base. The basic strategy of the proposed method assumes that a base case data base of economic dispatch solution is established according to statistical average of system operation data of the daily demand curve. Solutions in the data base can either be calculated by the B-coefficient method or other existing methods in the literature.

Ramanathan [70], discusses another fast solution technique for economic dispatch, based on the penalty factors from Newton's method. The algorithm uses a closed form expression for the calculation of Lambda (Lagrangian multiplier). It takes care of total transmission loss changes due to generation change, thereby avoiding any iterative processes in the calculations. In this algorithm, a major portion of the calculation time is spent on performing penalty factor calculations and is the same regardless of the calculation technique. Since, no iterations are involved, there are no oscillations or convergence problems in the execution of the algorithm.

Mamandur, et al. [71] introduce a method based on the Newton-Raphson theory to determine the optimal shift in power flow related to contingency states, or overload conditions in the system. The approach incorporates the generalized inverse solution method for rectangular matrices and the minimization of the cost incurred in shifting the generations. The triangular factors of the Jacobian matrix of a Newton-Raphson load flow model is used in the authors' method.

Isoda [72] recognizes the response limitations of generation units in the mix and assesses its impact as well as the impact of short term load forecast on the economic dispatch scheme. The author claims that with short term load forecasts available, the manual operation (by operator) to regulate the power generations of the thermal units, when the load changes steeply for a long time, is reduced. According to the authors, the optimum forecast period is approximately one hour in which the load demand should be forecast for a total of 4 to 6 points. Application of the method is also possible in an on-line dispatching control in electric utilities. Innorta, et al. [73] discuss a method of redefining the optimal and secure operation strategies (a very short period) in advance by exploiting the availability of the on-line state estimation and load forecasting. An "Advance Dispatching" (AD) activity is added in the system control hierarchy between the day before scheduling and the on-line economic dispatch. The authors prove that AD can be very effective for supplying security constrained participation factors to the regulating units when economic dispatch is operating and also improves system operation when economic dispatch is not available. The authors use an on-line parametric linear programming algorithm for the AD model.

Fox, et al. [74] proposes a method which allows the operator to strike a balance between the cost of holding emergency reserve and the cost to consumers of possible loss of load. The authors determine the cost of the expected power outage of each generator, that being a function of the failure rate. Then for comparison, they determine the cost of holding emergency reserves. Brazell, et al. [75] present a computerized algorithm of scheduling generation for contingency load flows, used in planning studies, taking into account the operating constraints such as economic dispatch and regulating reserves.

Viviani, et al. [76] present an algorithm to incorporate the effects of uncertain system parameters into optimal power flow. The method employs the multivariate Gram-Charlier series as a means of modeling the probability density function which characterize the uncertain parameters. The sources of uncertainty are identified as those emanating from long and short term forecast errors; measurement or telemetering errors and system configuration error. The energy system parameters are grouped into state vectors and control vectors. The Gram-Charlier series is employed to statistically model the control vector, which consists as elements, the generator power and voltages at each bus. Carvalho, et al. [77] follow the authors of reference [25] in representing the generation-transmission system as a network. The method used by these authors is unique in that they make use of a transportation model in the active optimal power flow and use an algorithm based on the generalized Upper Bounding approach. The method has been tested successfully on the IEEE-24 reliability system.

Sun, et al. describe in reference [78] and later in an EPRI report [79] the use of an explicit Newton approach for solving the OPF problem. The authors contend that for a given set of inequalities, a Newton OPF converges to the Kuhn-Tucker conditions in a few iterations. The major challenge is in identifying the binding interactive techniques for this purpose. Once the binding set is known, the problem can be solved in three or four iterations. The authors test their method on three different proven networks: a 912-bus, a 966-bus and a 740-bus system.

The Newton's method was also successfully tested on the Taiwan Power System as reported by Sun, et al. in [80]. Use of the Newton's method in minimization of the Lagrangian is also shown by Santes et al. [81]. The authors formulate a dual augmented Lagrangian for both equality and inequality constraints.

### ECONOMIC DISPATCH IN RELATION TO AGC

The role of Automatic Generation Control (AGC) is to maintain desired megawatt output of a generator unit and control the system frequency. The AGC also helps to keep the set interchange of power between pool members at predetermined values. Highly differing response characteristics of units of various types, e.g., hydro, nuclear, fossil, etc. are used for the control. The AGC loop maintains control only during normal (small and slow) changes in load and frequency. Adequate control is not possible during emergency situations when large imbalances occur.

In the following discussion of available literature on economic dispatch in the perspective of AGC, some of the problems faced by utilities are brought out and their proposed solutions given by different authors are presented.

Carpentier [82] reviews the potential applications of modern proposals for AGC as opposed to the conventional methods. The conventional implementations generally use integro-proportional control derived from the servo-mechanism theory. The modern proposals employ optimal power flow techniques. The author discusses the primary, secondary (LFC) and tertiary (ED) controls in a single system using conventional AGC. During the tertiary control, economic dispatch holds the cost curves in its memory, receives the electric power of these units and computes the economic participation factors for each unit, in order that resulting operation should be the most economic possible. In the modern AGC systems, optimal power flow techniques may be combined with results of optimal control theory to further increase the quality of the transients.

Shoults, et al. [83] present a computationally efficient method for including the area import/export constraints or power transfer limits in the multiarea economic dispatch procedure. The total interchange for each area within a pool are taken to be within some determined limits and total pool generation is considered to be equal to the total pool load. In a follow-up paper, Helmick and Shoults [84] discuss the development and implementation of a method which calculates individual operating company Area Control Error (ACE) requirements using limited computer resources without the benefit of an energy management computer system. Their method features a sorted-table approach to economic dispatch and calculates the ACE every five seconds

Podmore, et al. [85] recognize the reduced percentage of system capacity serving regulation duty during pool operation, and proposed control of jointly owned units as a feasible solution. The method has been implemented in utilities in Iowa and Nebraska.

In a series of papers published over a four year period, Zaborszky, Singh, Mukai, Kambale and Spare, have investigated the problem of AGC in three stages, namely: estimating [86], optimization [87], and control [88]. In the first of these papers Zaborszky, et al. [86] estimate the area load and its deviation from the area generation. In the second paper of this series, Mukai, et al. [87] discuss a three-stage dispatch targeting algorithm with each stage drawing on the results of the preceding stage. Stage 1 dispatch algorithm optimally distributes the scheduled load among available generating units and assigns a 24-hour schedule to each unit. Stage 2 dispatch algorithm optimally distributes the daily load schedule plus the residual load In a different but related paper, Zaborszky et al. [89] discuss dispatched control for reactive power and for HV-DC system.

The authors introduced a dispatched control principle for fulfilling the normal control responsibilities, such as generation and transmission at minimal total cost, maintaining frequency (plus synchronous time), tie-line loads, etc. The authors employ digital control methodologies and a new "Transjection Model" for the compound HV-AC-DC system.

In a review of the operating problems faced by interconnected utilities, the IEEE Working Group on Current Operation Problems [90], present problems of regulation in view of the North American Power Systems Interconnection Committee (NAPSIC) requirements. Some probable solutions are also provided. Kwatny, et al. [91] have identified some important issues regarding AGC. These are the coordination of dispatch and regulation functions to eliminate unnecessary unit cycling; the improvement of load tracking through the predictions initiated at both the dispatch and regulation levels. A coordination control level is devised which supervises the coordination of of the second in functions of AGC.

Taylor, et al. [92] have developed a stochastic simulation model for comparisons of AGC performance with real-time system data. The authors discover a high correlation between system frequency and the area control error throughout the 0.5-15 cycle per minute spectrum. Their comparisons indicate a little or negligible deadband effect in the process.

Glavitsch, et al. [93] discuss AGC and interfaces among the components of AGC. The authors explore the feasibility of using optimal load flow for such real time applications as load frequency control and unit control. Ng [94] develops a set of Generalized Generation Distribution Factors (GGDF) to replace the Generation Shift Distribution Factors (GSDF). According to the author, the GSDF are limited in their application due to the fact that they are only useful for determining line flows when generation are shifted, whereas the GGDF may be used independently to establish line flows for different system generation levels.

Nanda, et al. [95] develop a linear discrete-time state space model for a two-area hydrothermal system. The authors state that the maximum frequency deviation in any area out of the two, is more due to a step-load perturbation in the remote area than any similar perturbation in its own area. Also the optimum integral gain settings obtained in the continuous-mode AGC are not acceptable in the discrete-mode.

Kumar, et al. [96] discuss the application of a modified version of the Variable Structure System (VSS) concept. The proposed algorithm requires only two measurable variables, i.e., frequency deviation and deviation in tie-line power. According to the authors, the system performance with the VSS controller is much superior to any of the other concepts, such as the integral control or the proportional control or a proportional-plus-integral control. As an extension of their preceding work the same authors report in reference [97] results of a study of the load frequency control problem in the discrete domain using a mixed continuous and discrete model. The power system is modeled as a continuous system, while the controlfer is discretized. The authors include system non-linearities such as generation-rate constraint and governor deadband in their simulation studies.

Geromel, et al. [98] describe their new design procedure for load frequency control (LFC) which satisfies all classical requirements, as well a some additional requirements on the feedback control structure. Some of the requirements are: ACE, transient behavior, dispatch conditions, local control, etc. The authors solve a Ricatti equation iteratively until all the requirements are satisfied. The LFC problem is constructed as a quadratic objective function, which is to be minimized, to find an optimal feedback gain matrix.

Kusic, et al. [99] present some practical approaches for dispatch and unit commitment of areas with wholly-owned or commonly-owned units. Each owner of the commonly-owned unit (COU) receives power through tie-lines with the operating owner of the COU. One way of achieving thermal optimization for COU's is the operating owner maintaining two sets of fuel cost curves. Total curves are used for wholly-owned units and proportional curves are used for all shares of internal and external COU's.

Lotfalian, et al. [100] describe the transient phenomena associated with loss of generation contingencies. The authors develop equations that describe the inertial, governor, and AGC/economic dispatch load flows. They also present a method for determining the subset of generators that experience peak frequency excursions above 0.036 Hz and thus participate in governor load flow. Shahrodi, et al. [101] develop an AGC model for multi-area, multi-unit systems to study system dynamics with and without the effects of non-linearities. Using an eigenvalue analysis, critical modes are identified and related to system control loops. The authors also present methods to improve the stability of the system through increasing the damping of the critical modes.

The development of an Integrated Real-time Closed-loop Controller (IRCC) is discussed by Kuppurajulu, et al [102]. The IRCC performs the functions of economic load dispatch as well as automatic generation control. During emergency condition, the IRCC keeps track of the overload values. The synthesis between load dispatch and AGC is based on a logic whose main objective is to dynamically steer the system variables and Lagrange multipliers, so as to satisfy the Kuhn-Tucker conditions of optimality. The IRCC performs fast calculations using SCADA measurements.

## **DYNAMIC DISPATCH**

Economic dispatch may sometimes be classified as a static optimization problem in which costs associated with the act of changing the outputs of generators are not considered. On the other hand, a dynamic dispatch is one that considers change related costs. With the use of steady-state operating costs in the static optimization, poor transient behavior results when these solutions are incorporated in the feedback control of dynamic electric power networks. The dynamic dispatch method uses forecasts of system load to develop optimal generator output trajectories. Generators are driven along the optimal trajectories by the action of a feedback controller.

Carpentier [103] discusses the separability of dynamic dispatch from the conventional economic dispatch. Dynamic dispatch, or very short term scheduling computes real power over a finite period, minimizing the period operating cost, while meeting some instantaneous constraints such as power ramp limits, special nuclear requirements, etc. On the other hand the economic dispatch attempts to compute the real power, minimizing the operation cost while meeting constraints such as real power balance, and often transmission security. Separating the two types of dispatch renders the problem to a faster solution.

Ross, et al. [104] discuss the application of a dynamic economic dispatch algorithm to AGC. When coupled with a short term load predictor, look-ahead capability is provided by the dynamic dispatch, that coordinates predicted load changes with the rate of response capability of generation units. The dispatch algorithm also enables valve-point loading of generation units. The method that the authors use in their dispatch algorithm makes use of successive approximation dynamic programming. The authors claim that the algorithm is an improvement over the existing dynamic dispatch algorithm.

Raithel, et al. [105] introduce a successive approximation dynamic programming to obtain the optimal unit generation trajectories that meet the predicted area load. They use "dynamic" optimization as compared to the "static" case, as the dispatch program determines the economic allocation of generation for the entire future period of interest, using knowledge of both the present and the predicted load. The look-ahead capability provides the advantage of responding to sudden severe changes in load demand. They adapt the successive approximation dynamic programming algorithm to handle valve-point loading of units. Valve-point loading is accomplished via function.

# DISPATCH WITH NON-CONVENTIONAL GENERATION SOURCES

Non-conventional generation sources, such as solar photovoltaic, solar thermal, wind, geothermal, storage battery, etc. can become attractive alternatives to fossil plants. Many utilities strongly feel that a number of these non-conventional sources of energy can ease the critical future problem of fuel cost and availability. Much of this optimism is delimitated by the fact that such generation sources are known to produce extraneous operating problems in the power system as a whole. The existing conventional generating units, through use of AGC, are capable of operating under the dynamic response required to supply the random variations in system load. Such is not the case with grid-connect photovoltaic or wind generation systems. Frequent weather changes may translate into extremely high variations in the power generation from these plants. If the plant is constantly connected to the distribution system, this causes operational problems like, load following, spinning reserve requirements, load frequency excursions, system stability, etc., which the conventional AGC is unable to handle. The following is a discussion of a part of the literature existing on this particular subject.

Yau, et al. [106] discuss the use of storage batteries as a complement to the expensive fossil plants for the purpose of regulation. The authors have utilized a hybrid simulator to study the effects of regulating batteries on power system dispatch. These batteries can also be used in peak shaving or load leveling mode. The authors used two sodium-sulfur battery banks each rated at 250 MW. It is concluded that batteries used for regulation improves the Area Control Error (ACE) significantly.

Lee, et al. [107] have investigated the load following and spinning reserve penalties for intermittent generation in the economic evaluation of such sources in the presence of a conventional generation mix. They present an approach estimating the load following and spinning reserve requirements for a power system containing intermittent generation. They incorporate this in an optimal generation expansion planning model which evaluates the effect of intermittent generation mix and the production costs. The authors claim that the penalties are too high due to the presence of intermittent generation, and that all energy and capacity credits are eliminated due to such penalties. According to a case study performed by the authors, increasing penetration of intermittent generation (wind powered system in the case study), causes an increase in the spinning requirements and the load following requirements, the increase being linear. The effect of penetration on system costs is found to be nonlinear. For their case study below 5% penetration, the load following requirement is satisfied by the optimal generation mix, the penalty cost arising primarily due to increase in spinning reserve requirement is greation, the load following requirement begins to alter the generation, the load following requirement begins to alter the generation mix, with the combined effect of higher spinning reserve and the departure from the optimal generation mix, imposed by the load following constraint.

Zaininger, et al. [108] present results of a dynamic study of minute-to-minute ramping, frequency excursions and short-term transient stability of a power system containing wind power generations. The authors determine the allowable combined wind turbine (WT) cluster corresponding to a 0.1 Hz and a 0.4 Hz frequency excursion. The allowable W cluster output change for specific load changes is also determined. Curtice, et al. [109] also analyze the effects of integrating WT's with the utility's power system. Specifically, the effect on the load frequency control process, under the performance criteria set by the North American Electric Reliability Council Operating Committee, is investigated by the authors. Using a 6 MW per minute system response rate, the authors found that increased control effort was necessary for WT output variations of over 2 MW. This variation also caused a deterioration in system performance (ACE values).

Schlueter, et al. [110] discuss the modification of unit commitment, economic dispatch, regulation requirement and frequency excursions, when the wind penetration level is significant. The authors demonstrate the effects of modifying the response capability of regulation and load following controls, which the authors content, must be modified to exploit the changes in spinning reserve, load following and unloadable generation capability provided in the unit commitment procedure.

Simburger [111] presents results of simulating the operation of a power system consisting of the generation system and the AGC in response to changes in net demand as well as variations in wind farm generations. The authors conclude that new dispatch techniques will be required to accommodate intermittent generation technologies. In their simulations with WT clusters, the authors provided extra ramping capability by placing at least 500 MW of hydro capacity under AGC for a 24-hour period. The effect of WT penetration is also manifested in an increased inadvertent interchange. Chan, et al. [112] develop a probabilistic method to quantify the load following, operating reserve and unloadable generation requirements for a utility with one or more spatially dispersed WT clusters. With this method the utility decides on the risk of exceedance of the ramping capability that it is willing to accept through use of the standard deviations of the rate of change in total wind generated power. The 10-minute operating reserves and unloadable generations are also computed in a similar fashion.

Sadanandan, et al. [113] discuss yet another set of investigative results on the impact of wind generation on the operations of the Tennessee Valley Authority. The authors represented each WT by a synchronous generator having a rated output equal to the rating of the WT itself. The maximum allowable change in wind generation is found to be 20 MW per minute, considering the total regulating capacity of 50 MW per minute. Besides, ACE excursions are found to frequently exceed 135 MW with 15% penetration of wind generations, compared to a normal ACE excursion of the order of 100-150 MW.

Bose, et al. [114] examine the impact of new generation technologies on utility operation practices. While not dealing extensively with any particular technology, these authors discuss the general characteristics of each potentially viable new generation source. The scheduling practices considered in the paper range from load frequency control and economic dispatch to the weekly (short term) and yearly (long term) scheduling of generation units. The impact of new technologies is predicted to be significant, the exact effects depending on the level of penetration, the extent of dispersion, ownership, and the weather dependency of the technologies elected.

Chalmers, et al. [115] present results of the impact of photovoltaic (PV) generations on the operation of a utility. The authors believe that although substantial amount of PV generation can be integrated into the utility system, the most severe condition is created by the sudden change in PV generator output when the entire array is completely covered or uncovered by a fast moving cloud bank. It is also concluded that PV penetration exceeding 5% causes the conventional generation some difficulty in tracking these rapid PV output changes.

David presents in references [116] and [117] some probabilistic methods for assessing the impact of intermittent generation sources on short range system operation. The author defines three types of variations in output from a wind generation system, depending on the time scale of analysis. He then derives conditional probability which are used to estimate the spinning reserve and ramping rate requirements, and frequency deviations.

Javid, et al. [118] specify three control regimes for the operation of wind turbine (WT) clusters in coordination with the generation mix of a utility. These regimes are open loop, feed forward and closed loop controls. In the first type of control maximum wind energy is captured and is used as "negative load". In the second type of control strategy, the rest of the generators are required to change generations to accommodate the wind generated power and in the third, WT output is changed in order to reduce frequency excursion.

Vachtsevanos, et al. [119] develop two computer-based models for the interconnected operation of WT clusters with a power system. These methods are a load flow simulation technique and a frequency control simulation program. The first method leads to the identification of a particular grid bus where, if the WT cluster is connected, results in an optimum voltage distribution. The second method computes the allowable load variations with the WT output considered as "negative load".

In another paper of similar nature the same authors [120] view the dispersed generator as an active device contributing towards the regulation of real and reactive power flows while improving overall system stability. By designing appropriate interface equipment and control strategies, the authors prove that the resulting reduction in load following requirements for conventional units improve the power quality and the stability of the interconnected system.

Chowdhury [121] introduces a new operational tool for integrating a photovoltaic (PV) system into the utility's generation mix. A modified dynamic dispatch algorithm is proposed which requires a Box-Jenkins time series method for forecasting short-term PV output. The dispatch consists of a rule-based algorithm which control the non-committable generations to achieve an optimal solution. The rule base works in tandem with a conventional dispatch routine.

### CONCLUSIONS

A general survey of papers and reports addressing various aspects of economic dispatch has been presented in this paper. The time period covered is 1977-88. Four important classifications of economic dispatch are identified and the papers are grouped under these classes. These areas are:- (1) optimal power flow, (2) economic dispatch in relation to AGC, (3) dynamic dispatch and (4) economic dispatch with non-conventional generation sources.

We have tried to include as much descriptions of the contents as possible in order to include the important and unique aspects of each paper. Some interactions among papers by the same authors over the period or among similar papers by different authors are presented to the extent that is allowable within the limitations of a single paper. Our attempt is not directed at evaluating and comparing relative performances of the existing algorithms but at presenting a clear picture of what is available so that a researcher in the area of generation dispatch can identify problems and seek their solutions.

It is fairly obvious from this survey that optimal power flow has received a great deal of attention over the past two years or so. It is our belief that this trend will continue as long as faster computers keep evolving and more efficient optimization algorithms are utilized. It is now generally recognized that the reduced gradient method of Dommel and Timmey is not the most effective in solving the OPF atthough twenty years ago, it was considered the state of the art. Since then, many authors have formulated and implemented more efficient and accurate algorithms; the only difference in the performance of these was the convergence property. Some authors have suggested quasi-Newton method and explicit Newton methods while others have used sparsity oriented techniques like the Hessian-based algorithms. Real-time solutions of the OPF is one area gaining a lot of momentum in the past few years. Such a solution implies the minimization of instantaneous cost of active power generation on an operating power system subject to preventing violations of operating constraints in the event of any planned contingencies. Such an on-line implementation requires fast execution times and minimum storage allocations. Undoubtedly, these

Another important area of future research is answering multitudes of questions regarding the impact on OPF of incorporating non-conventional generation (NCG) sources into the generation dispatch strategy. With the NCG's providing random input into the system, it becomes a matter of careful statistical study of all variables involved.

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### DISCUSSION

D. P. Kothari (Royal Melbourne Institute of Technology, Melbourne, Australia): I wish to commend the authors for their valuable contribution in providing an excellent review of recent advances in economic dispatch. I would like to add some more recent papers in this area.

Not only economic dispatch but unit commitment and optimal hydrothermal scheduling have been covered in books [1,2]. Reference [3] deals with application of progressive optimality algorithm to optimal hydrothermal scheduling in presence of pumped storage plants considering deterministic and stochastic data. Reference [4] presents a new approach to economic emission load dispatch through goal programming techniques. A New Optimal power flow algorithm [5] has been developed using Fletcher's quadratic programming method. Reference [6] presents a review of recent advances in optimal hydrothermal scheduling. Reference [7] deals with discrete-mode AGC of an interconnected reheat thermal system considering a new area control error based on tie-power deviation, frequency deviation, time error and inadvertent interchange.

Once again I congratulate the authors for their very timely and useful contribution.

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Norton Savage (U.S. Department of Energy, Washington, D.C.):

The comments expressed here are those of the

writer, and do not necessarily reflect the views of the U.S. Department of Energy.

The authors have accomplished two worthwhile tasks. First they have culled the literature to find a long list of works dealing with economic dispatch. Second, they have digested their research and briefly stated the thrust of each item on their list. The annotated bibliography they have produced will be useful indeed to electric system planners and operators.

Using the subject categories of the paper, it appears to me the references can be grouped as follows:

Optimal Power Flow - items 17 thru 81

Economic Dispatch/AGC - items 82 thru 102

Dynamic Dispatch - items 103 thru 105

Economic Dispatch/Unconventional Sources - items 106 thru 121

Items 4 through 16 appear to be textbooks that either include economic dispatch as one of several power system topics, or focus closely on it as the major topic. Item 1 is Harvey Happ's outstanding 1977 survey, which I was driven to read again upon finding it cited here. And items 2 and 3 are IEEE Working Group Surveys, well worth having as basic references.

If the relative number of reference is taken as a measure of the importance attached to each category, Dynamic Dispatch appears to be of least value as a subject for study. Is this a valid inference or is the topic too new to have yet attracted much attention? Economic dispatch as related to Automatic Generation Control and to Unconventional Sources appear to be of equal interest to system engineers. Of course unconventional sources (taken to be batteries, fuel cells, windpower and photovoltaic assemblies) are in the very early stages of power system penetration and do not yet contribute much in the way of power or energy. Optimal Power Flow, being a natural extension of pure unconstrained economic dispatch (allocation of load among generators for minimum fuel cost) has had a 'long history of development, and therefore can be expected to provide many reference papers.

The advent of Cogeneration, Small Power Producers (SPPs) and Independent Power Producers (IPPs) as generating sources to be considered by system engineers is fairly recent. As time goes on these sources could well become of greater importance, and their effects on system operation may not be negligible. It is claimed in some news reports that some of these power sources are (or will be) dispatchable. Have the authors noted any papers dealing with the problems of optimal power flow when non-dispatchable sources of unknown reliability are added to a system with generators whose reliability is known (at least probabilistically)?

Dispatch of cogeneration sources by a utility control center raises the problem of conflict between manufacturing needs of the cogenerator and power production for the utility. Utility dispatch of SPPs and IPPs appears feasible but may not be necessary if such capacity is small compared to the utility's own capacity. But for large IPPs there may be a problem, as the economic incentive of an IPP owning one or two units is to sell the most power he can produce. This objective may not coincide with the utility's need to operate a balanced system under contingency and reserve constraints. Have the authors found any papers on this topic?

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Badrul Chowdhury and Saifur Rahman. The authors would like to thank Mr. Norton Savage and Prof. D. P. Kothari for their interesting comments and a few questions. The large number of papers in the

areas of optimal power flow and economic dispatch/AGC indicates the level of historical interest in this area. This has been driven by the need to operate the utility-owned generation in the most optimum way. The need for dynamic dispatch is beginning to be felt due to the additional constraints that are now being placed on the system. Because this topic is new there is not yet a large body of literature addressing this subject. However, with the advent of cogeneration, the presence of third party owned generation is now being felt by the electric utility operators. Mr. Savage is absolutely right in pointing out that the traditional practice of economic dispatch cannot be equitable to the interests of both the utility and the cogenerators. We are aware of research activities in this area, but have not found any published paper specifically addressing this topic.

We appreciate Prof. Kotheri's efforts in adding seven citations to our list of 121 references. While we made our best efforts to include as many relevant articles as possible, undoubtedly some good papers were left out, especially the three that were published after our paper was submitted.

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