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# A Review of Maintenance Scheduling Approaches in Deregulated Power Systems

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*Abstract*- **Traditionally, the electricity industry is fully regulated with a centrally controlled structure. The power system operator has full technical and costing information as well as a full control over the operation and maintenance of power system equipment. Recently, many countries have gone through privatization of their electricity industries unbundling the integrated power system into a number of separate deregulated business entities. The preventive maintenance of power system equipment in the restructured electricity industries is no longer controlled centrally, and none of these entities currently have explicit accountability for maintenance activities. The approaches used to schedule the maintenance activities in the centralized system are not ideal for addressing the new deregulated environments. In recent years a few research publications has been reported in this area. This paper presents a review and analysis of these reported maintenance scheduling approaches for power system equipment in the changed environment.**

*Index Terms*— **Maintenance Scheduling, Deregulated Power System, GENCO, TRANSCO, Coordination.**

## I. INTRODUCTION

IN order to avoid premature aging and failure of power system equipment leading to unplanned and costly power outages, it is important to carry out preventive maintenance at regular intervals. By the term 'power system equipment' we are mainly referring to generators and transmission lines in this paper. The power system equipment maintenance involves scheduling and executing the actual maintenance works. This is vital for the planning of the secure and reliable operation of a power system, primarily because other short-term activities are directly affected by such decisions [15,22,28]. The goal of maintenance scheduling in a power system is to allocate a proper maintenance timetable for the power system equipment while maintaining system reliability, reducing total operating cost, extending equipment life time etc.

Traditionally, the electricity generation, transmission and distribution industries have been fully regulated with a centrally controlled structure. The operator has a full control of the power system as well as complete technical and costing information of each operation and maintenance activity, and solves the maintenance scheduling problem centrally [2,5,8-10,12-15,18,19,22-24,20].

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In the last decade, however, the electricity industries in many countries have moved away from centrally controlled structures, unbundling the integrated power system into three main segments: generating companies (GENCOs), transmission companies (TRANSCOs) and Distribution companies (DISCOs) [11,26,28,29]. An independent system operator (ISO) operates a power system and these three business entities participate in the trade through it. The changes are not only associated with electricity market participation but also affect the optimal operation of power systems requiring a range of new issues to be addressed [11]. The preventive maintenance of power system equipment is no longer controlled centrally, and none of these entities currently have explicit accountability for maintenance activities [4,28,31]. Furthermore, in modern power systems the demand for electricity has increased with related expansions in system size, which has resulted in higher numbers of generators and transmission lines, and lower reserve margins making the maintenance scheduling problem very complicated [1,4].

In recent years researchers have focused much attention on new theoretical and methodical approaches for coordinating and optimizing maintenance activities in deregulated power systems. Over the last few years a number of research publications have been reported on power system maintenance activities addressing some of the power system deregulation issues. This paper reviews and analyses the proposed maintenance approaches in the literature to short-term and long-term maintenance scheduling of generators for GENCOs and transmission lines for TRANSCOs, and their coordination in a liberalized electricity market. The formulation of problems and the methodologies of solution are discussed and analyzed.

The next section reviews the maintenance scheduling problems and solutions in a centralized power system to provide a background to the maintenance problem. Section 3 first introduces the operation of power systems in the restructured environment, and discusses the issues with maintenance scheduling in the liberalized electricity market. It then focuses on the review of literature on the maintenance scheduling approaches for short-term, long-term and co-ordination. The final section summarizes the paper and its conclusions.

## II. MAINTENANCE SCHEDULING IN CENTRALISED POWER INDUSTRIES

### A. Problem description

In the regulated power system, which still exists in many developing countries, a centralized maintenance schedule is produced coordinating with other planning activities using the complete costing and technical information. The power system equipment maintenance scheduling problem is a large scale problem, which includes long-term and short-term scheduling and coordination of maintenance activities of generators and transmission systems [12,13,15,24,25]. In many cases the generator maintenance scheduling and transmission maintenance scheduling are tackled as separate problems, largely because of the complexity and information availability of the combined problem.

General maintenance scheduling is a multi-criterion constrained combinatorial optimization problem, with nonlinear objective and constraint functions [2]. There are generally two categories of objectives in centralized maintenance scheduling, based on reliability [2,8-10,15,19] and economic cost [2,5,12-14,18,22,24,25,30]. The leveling of the reserve generation over the entire operational planning period is the most common reliability criterion. This can be realized by maximizing the minimum net reserve of the system during any time period [15]. In the case of a large variation of reserve, minimizing the sum of squares of the reserves can be an effective approach [8-10]. Alternatively, the quality of reserve is considered, whereby the risk of exceeding the available capacity is leveled over the entire period by using the equivalent load carrying capacity for each unit and an equivalent load for each interval [15]. Minimizing the sum of the individual loss of load probabilities for each interval can also be a reliability objective under the conditions of load uncertainty and random forced outages of units [15].

The most common economic objective is to minimize the total operating cost, which includes the costs of energy production and maintenance [5,12]. If outage durations are allowed to vary, this results in a trade-off between the energy production cost and the maintenance cost. Shorter outage durations lead to higher maintenance costs but reduce the load of expensive generation and possible energy purchases, resulting in lower energy production costs. The production cost alone could also be chosen as the objective function by minimizing the total energy replacement cost due to preventive maintenance scheduling [18].

Any maintenance timetable must satisfy a given set of constraints. Typical constraints of the maintenance scheduling problem are:

- Maintenance window constraints, which define the possible times and the duration of maintenance for each piece of equipment.
- Crew constraints, which consider the manpower availability for maintenance work.
- Resource constraints, which specify the limits on the resources needed for maintenance at each period.
- Exclusion constraints, which prevent the simultaneous maintenance of a set of equipment.
- Sequence constraints, which restrict the initiation of maintenance of some equipment after a period of maintenance of some other equipment.
- Load constraints, which consider the demand on the power system during the scheduling period.
- Reliability constraints, which consider the risk level of a given maintenance schedule.
- Generation capacity constraints - specify the limit of generating units.
- Transmission capacity constraints, which specify the limit of transmission capacity in an interconnected power system.
- Geographical constraints, which limit the number of equipment under maintenance in a region.

### B. Solution approaches

Several deterministic mathematical methods and simple heuristic techniques are reported in the literature for solving maintenance scheduling problems [15,18,19,22,24,25]. Mathematical methods are mainly based on integer programming, branch-and-bound and dynamic programming. However these methods are unsuitable for the nonlinear objectives and constraints of maintenance scheduling and their computational time grows prohibitively with problem size [15]. The heuristic methods use a trial-and-error approach to evaluate the maintenance objective function in the time interval under examination. They require significant operator input and may even fail to find feasible solutions [2,15]. In order to overcome some of these limitations a number of soft computing based hybrid approaches for maintenance have been studied. These include evolutionary based approaches, fuzzy logic, simulated annealing, and their hybrids [2,5,8-10,12-14,30]. Most of these techniques, however, require appropriate parameter settings, and do not guarantee an optimal solution due to their stochastic nature.

## III. Maintenance Scheduling In Restructured Power Industries

### C. Operation of deregulated power systems

Deregulation of electrical industries, in many developed and fast developing countries, has caused significant structural and regulatory changes to their electric power industry [28,29]. In many situations generators (who produce electricity), suppliers (who supply the electricity to the end customers), and other traders can freely trade electricity in an open market. Now all market participants who wish to trade energy have to compete through one or many free markets, such as bilateral, power exchanges and balancing markets. The power system is operated by an ISO to balance supply and demand of electricity in real time [11,26,29].

An example of this is the New Electricity Trading Arrangement (NETA) currently operating in England and Wales, which has introduced full competition in electricity trading [11,26]. Within the NETA market structure there are three main segments; the contracts market, the balancing market and the imbalance and settlement process. In the bilateral contract sellers and buyers enter into transactions where the quantities traded and the prices are at their own discretion and not a matter for the ISO. These transactions are then brought to the ISO with a request that transmission be provided. If there is no congestion on the system the ISO simply dispatches all requested transactions and makes a fair charge for the services. The remaining power is traded through the balancing market (BM). The BM provides a centralized mechanism where generators and suppliers submit bids and offers to deviate away from contracted positions. The market operator utilizes available bids and offers firstly to ensure that supply meets demand and secondly to alleviate any network problems which may occur. A Balancing and Settlement Code (BSC) exists that sets out the rules for central balancing and governance and all market participants must be signatories of this.

Generally the ISO does not own any generators but has the responsibility for managing the balancing mechanism to maintain security and reliability of power systems. Markets govern operation and expansion, and in a world of competition, dispersed players make decisions that collectively affect system adequacy [1]. Generators not only have to optimize the allocation of their capacity across markets, but also select the timing of their sales in the forward markets. Transmission owners have to ensure recovery of the investment in assets, load-serving entities have to meet the need of consumer choice, and power marketers have to manage their exposure to risks [29].

Overall evaluation of generating system adequacy appears to be declining in the new utility environment despite the fact that severe power shortages have occurred, for example in California and Alberta, due to inadequate generating and transmission facilities [4]. The installed generating and transmission capacities should be capable of meeting the system load in the face of outages and scheduled maintenance of power system equipment [23,28].

### *D. Deregulation and Maintenance Scheduling*

The maintenance scheduling of power system equipment has changed drastically as the industry has become deregulated [1,3,4,6,16,17,20,21,23,27,28,31]. The situations are more complicated due to the diversities of the ownership of the equipment. Now all the unbundled entities (GENCOs and TRANSCOs) have their own objectives. Cost minimization is only a goal for these companies and the main priority may be to meet their contractual commitments. With market conditions constantly changing, scheduling around the market is a challenge. The market driven scheduling should consider the electricity prices rather than the operating costs, whilst still optimizing the maintenance activities. The facility owner tends to keep the facility running when the market price is high and perform maintenance only when the market price is low. In addition the facilities may be used to sell energy to other areas which have high loads (and high prices). Under such circumstances the decision of when to maintain a facility is driven by profit incentive rather than by the optimal cost of maintenance and repair. The increased volatility of market prices has made it even more difficult to select optimal times for maintenance. Volatile market prices also affect the ability to schedule outages in advance and diminish the level of confidence that the original outages will actually be followed [27].

In the deregulated environment a company has limited information on activity of other companies, which adds many uncertainties on its own planning decisions. Capacity shortages can be created by a lack of coordination in scheduling activities of different companies [4]. Therefore the scheduling activities require more coordination and communication among different entities. A coordinating stage is usually included in scheduling procedure to study the feasibility of the schedule and its optimality for the benefit of all [31].

In the following subsections we review the problem formulation and solution approaches reported in the literature for GENCOs' generator maintenance scheduling, TRANSCOs' transmission maintenance scheduling and coordination between them.

### *E. Generator Maintenance Scheduling Problem and Solution*

In the deregulated system the most common objective of the generator maintenance scheduling for a GENCO is based on economic criteria [6,17,20,21,23,28,31]. Most of the authors formulated the optimization to maximize the income, which is revenue minus the production cost and maintenance cost. From the view point of maintenance the objective can be to minimize the sum of maintenance cost plus the loss of revenue due to the planned maintenance outages [17,31]. The other objective function that has been considered by a number of researchers is based on reliability and security [1,4,6,28]. This is more important for the ISO, who has the responsibility of operating and maintaining the system. GENCOs, however, have interest in the reliability objective of keeping their system healthy in order to meet their contractual commitments. The reliability objective in this case is directly related to the economic criteria.

Many constraints related to the deregulated generator maintenance scheduling problem have a similar formulation to that of the centralized system, such as maintenance windows, crew/resource availability, and equipment/power system related constraints. In addition to these the schedule should also take into account market constraints such as contractual commitments, maintenance policy and electricity market rules [3, 27-29].

Shahidehpour and Marwali are leading researchers in addressing issues of maintenance scheduling in deregulated electricity industry [21,23,28]. The authors' book [28] published in 2000 and other research papers provide their research work on the modeling and optimization of short-term and long-term maintenance scheduling problems, and their coordination in a liberalized electricity market [7].

In a chapter in [28], Shahidehpour and Marwali tackle long-term generator maintenance scheduling problem for GENCOs. The generator maintenance scheduling problem was formulated as potential revenue optimization while meeting constraints such as maintenance windows, crew availability, load demands, as well as technical issues related to the generators and power system. Stochastic outages of the generator have been taken into account in the models, using probabilistic force outage rate. The authors also attempted to coordinate the long-term and short-term generator maintenance scheduling problems in the deregulated system [28]. The short-term problem is first embedded within a long-term maintenance scheduling formulation. The long-term maintenance scheduling determines specific maintenance windows and the short-term problem checks the possible short-term commitments and dispatch of the available generators in a dynamic scheduling environment.

Hayashi et al. also considered a long–term generator maintenance scheduling problem for a GENCO [17]. The problem was to determine the best maintenance time intervals, within one year, to take generators off-line for planned maintenance by minimizing the total operating cost of the GENCO, while its ISO meets the power demand and system reliability.

Xu and Kezunovic in [31] formulated the maintenance problem as a mixed integer programming problem to minimize costs associated with maintenance and loss of revenue with typical constraints.

The authors of three applications described above [17,28,31] employed the Benders Decomposition method by de-coupling the whole scheduling problem into one master problem and several sub-problems. The master problem is a relaxation of the original problem with a subset of constraints. The relaxed constraints are considered in the sub-problems, which generate infeasibility cuts to the master problem. The resulting algorithm involves iterations between sub-problems and master problem until the solution converges or no solution conclusion is reached.

For the maintenance scheduling applications [17,28,31], the master problem is solved at the GENCO's side, whereas each sub-problem represents a set of constraints imposed by the ISO or a third entity. The infeasibility of the ISO sub-problem was added as Benders cut to the master problem in subsequent iterations. Xu and Kezunovic have employed mobile software agents to communicate between the master and sub-problems [31].

Kim et al. 2003 formulated generator maintenance scheduling as a dynamic multi-stage non-cooperative game in the competitive market [20]. The individual GENCO is modeled as a profit seeking player. Each player seeks to maximize their cumulative profit from the energy action over a scheduling period. One of the main components in determining the cumulative profit is the maintenance strategy. Each GENCO tries to set up the optimal maintenance period of their generators in a sequential fashion. The optimum strategy of a GENCO is defined by the Nash equilibrium of the game [20].

A number of maintenance management strategies are suggested for GENCOs to control maintenance activities in market environment, emphasizing on use of the computer based maintenance management system in [3,27]. Bier and Glyer [3] focus the reliability–centered maintenance in the view of importance of reliability of power system equipment on the profitability of the company. Usually the forced outages have direct financial consequences for the utilities as they may affect the cost of required reserves to cover possible forced outages.

Chattopadhyay [6] presents an analytic model to assess the maintenance needs of generating units in a competitive electricity market. The paper proposes a stochastic optimization framework to optimize the selection of maintenance items over the life of generator to maximize the net revenue earning of the unit. The author developed a mathematical model taking account of different costs associated with maintenance. These costs include direct maintenance expenses, opportunity cost such as foregone market revenue, replacement costs and penalties for not meeting contractual obligation. The model also recognizes the technical issues of maintenance such as degradation of unit, forced outage rate, random outages. The paper demonstrated the use of the model to analyze the optimum trade-off between short-term revenue maximization and long-term health and productivity of generating units in a simple example.

Billington and Abdulwhab [4] discuss a hybrid approach for a short-term generator maintenance scheduling in a competitive power market. The methodology combines deterministic criterion within a probabilistic framework. The scheduling objective is to ensure the resulting risk does not exceed a predetermined acceptable level. In a deterministic approach, the acceptable margin is either a percentage of the available capacity or load, or a value equal to the largest loaded unit. This methodology is designated as the health levelization technique. It creates maintenance schedule for participating GENCOs that satisfies a specified health criteria for the entire period under study. The authors demonstrated the effect of conducting preventive maintenance with different load profiles.

### *F. Transmission Maintenance Scheduling Problem and Solution*

Shahidehpour and Marwali have considered short-term and long-term transmission maintenance scheduling problems in deregulated system in a number of publications [21,23,28]. The authors formulated and solved long–term transmission line maintenance scheduling problem for TRANSCOs in a similar fashion as for GENCOs in their book [28]. The problem was to maximize the potential revenues while meeting maintenance and technical constraints. Again stochastic outages of the transmission lines have been taken account into the models using force outage rate.

Short-term transmission line maintenance scheduling is considered in [23,28] by introducing loss of revenue as the objective function while satisfying transmission and voltage constraints. As canceling a transaction or purchasing reactive power relates to the loss of revenue, the trade-off between maintenance costs and revenue loss is optimized in the proposed application. A decomposition approach on duality theory has been proposed, which consists of a master problem for maintenance program and sub-problems for transmission and voltage problems. The master problem solves the short-term maintenance and the subproblem checks the operational (line flow and voltage) constraints for the proposed maintenance solution. If violations are observed in the subproblem, Benders cuts will be set up and added to the master problem to generate a revised solution.

The same authors attempted to coordinate the long-term and short-term transmission scheduling problems in the deregulated system using the Benders Decomposition method [21,28]. The long-term scheduling period (one year) is divided into weeks and a maintenance strategy for the weeks is derived. The objective function of the long-term scheduling problem formulated using two terms: weekly transmission costs and the expected loss of revenue due to line maintenance. This is subject to the maintenance windows, crew and resource availability and power balance constraints. The transmission network constraint has been relaxed in the long-term problem but has been considered in the short-term solutions. For the identified maintenance window from long-term solution the short-term (hourly) line maintenance is formulated to maximize revenue of the transmission provider while satisfying the power transaction, transmission contracts and system reliability.

### *G. Maintenance Scheduling Coordination*

The coordination of generator and transmission maintenance outages is very important in deregulated environment [4,16,28,31]. If the owners of the generators and transmission lines schedule their maintenance as they see fit, this can degrade grid reliability and impend market efficiency. The uncoordinated outages of transmission lines and generators usually disrupt the power generation and its export for a longer period than the coordinated activities. Coordination of generation and transmission outages pose potential financial impacts on the GENCOs and TRANSCOs. If a company is asked to schedule its maintenance at a time that is not financially beneficial for it, then the company may challenge this instruction [16].

As an independent entity responsible for the operation of power systems and maintain system reliability the ISO is the natural and suitable body for assuming the role of coordinator of maintenance activities. In many cases the task of synchronizing the overall activity is assigned to the ISO [4].

A typical maintenance scheduling procedure in deregulated environments involves planning, submitting and approving steps [28,31]. At first, GENCOs and TRANSCOs make their tentative schedules for the maintenance, and then submit them to the coordinating body, typically the ISO, for approval. The coordinating body checks the schedule for feasibility against the system constraints and overall coordinated optimality, and may ask the companies to modify their schedules with some feedback information. The proposed coordination assumes that GENCOs and TRANSCOs incorporate their maintenance activities through the ISO. However, different market structures exist. In a competitive market GENCOs and TRANSCOs are interested in optimizing their own maintenance schedules and may not always cooperate or disclose information between them and with ISO.

There is also a concern of coordination of the maintenance for individual generating units owned by different GENCOs. Billington and Abdulwhab [4] proposed a coordination technique between GENCOs' maintenance schedules though the ISO. Each GENCO provides a maintenance request for specified periods. The ISO gathers maintenance requests for all the GENCOs in a common period and determines an acceptable maintenance schedule for the generators of the participating GENCO. The resulted maintenance schedule satisfies a predetermine system reliability level. The risk of capacity shortage is avoided by having impending scheduled maintenance requirements.

## IV. CONCLUSIONS

The deregulation and competitive electricity market place have created some additional challenges for power system maintenance scheduling. Now reliability is more important to profitability that it used to be. Thus, avoiding a day of forced outage may be worth several days of planned outages at a low cost time of year. In recent years researchers have focused much attention on new methodical approaches for coordinating and optimizing maintenance activities in order to improve the economic posture of the GENCOs and TRANSCOs as well as the reliability of restructured power systems.

This paper has reviewed the different maintenance scheduling approaches for short-term, long-term and co-ordination as proposed in the literature. These formulations are mainly based on potential revenue maximization while meeting constraints such as maintenance windows, crew availability, load demands, as well as technical issues related to generators, transmission lines and power system. The ISO is proposed as a coordinator of the maintenance activities between different entities to check their feasibility and avoid capacity shortages.

The most common solution approaches in the literature are based on a mixed-integer program approach using Bender's decomposition method. Many optimization approaches, such as heuristic, expert systems and meta-heuristics, have been used to address centralized maintenance scheduling problems. However, very limited research reports on other alternative solutions and modeling methods for deregulated maintenance scheduling problems. Although it is difficult to say how good an approach is without comparing its performance with that of other alternative approaches, the decomposition approach seems logical due to the nature of deregulated power systems.

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