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Economic outage scheduling of transmission line for long-term horizon under demand and wind scenarios

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***Abstract*—A substantial increase in renewable energy in-feed to the primary grid as well as demand growth poses a challenge for transmission system operators (TSOs) to perform maintenance activities while addressing security of supply. A computationally efficient outage scheduling algorithm which is customizable in terms of area and time selection is proposed in this paper. Benders decomposition approach under different demand and wind scenarios, spanning two-stage stochastic programming approach is used. An accurate schedule while fulfilling both maintenance and network constraints is validated on a modified IEEE RTS-24 bus system in GAMS environment. A cost comparison analysis is also performed in this study.**

***Index Terms*—Benders decomposition, demand and wind scenarios, long-term horizon, outage scheduling, transmission line scheduling.**

I. INTRODUCTION

Recent innovations in renewable energy sources and their large scale integration in the power systems have a significant impact on the topology of the power system. Typically, the power system is summarized as generation, transmission and distribution system working together to provide the required energy demand to the different sectors of the society. The expansion of power system in 21st century is exponentially growing which is leading to an increase in transmission capacity of a power system. The demand side, on the other hand, is also increasing as people are largely shifting to green technology. To maintain the demand side supply and the generation side, a reliable transmission system should be incorporated and maintained to improve the society and have a balance power supply throughout the system. In addition to power balance, the transmission system operators (TSOs) will also cope with the continued increase in penetration of renewable energy, emergence of storage, electric car and the long-anticipated components replacement wave.

The transmission system has to get upgraded in terms of power transfer capacity and increase in network connectivity. Increase in transfer capacity leads to the expansion of existing grid topology, for instance building new transmission lines in the network. Apart from building new transmission corridor, TSOs also need to take care of the existing infrastructure by following a proper maintenance routine. Not to be forgotten, the transmission line is one of the most important components of the transmission system. Failure in transmission lines has a direct impact on the demand side as well as generation side of the power system. Large arguments have been made on different transmission assets that are as important as the transmission line, but it can be said that the transmission line is the most important component as its proper and uninterrupted working results in smooth working of other components. Other components such as insulators, transformers, bus-bars, protective devices are also important components of the power system, but in this research, we have specifically considered transmission line maintenance and not any other component of the transmission system.

Outage scheduling for maintenance in asset management of electrical transmission and distribution system plays an important role in power system reliability. With the increasing stress on the transmission assets, it has become important to study the reliability of the power systems. This need has given way to a new understanding of asset management [1]. Literature study suggests that asset management plays an important part in the transformation of the power system industry. For a complete overview and updated biblical survey, refs. [2][3] can be referred to. Decomposition approach was first introduced to solve maintenance problem with the most famous benders decomposition algorithm [4]. Application of benders decomposition for power plant scheduling was first observed in [5]. A deterministic approach for integrated generation and transmission maintenance scheduling with network constraint was first introduced in [6]. Introduction to long-term generation and maintenance scheduling with network fuel constraint using benders decomposition approach was proposed in [7]. Ref. [8] considered the market environment by using a bi-level approach in long-term transmission line scheduling. Most studies consider short-term transmission line maintenance, and hence this study did not look into that aspect. On the other hand, there exist some gaps in existing literature that needs to be addressed, such as:

- Integration of distributed generation subjected to exogenous uncertainty into the primary grid.

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- Unavailability of customizable tool for the maintenance of the transmission line in specific area and time. A customizable tool enables the user to check the flexibility and facilitate selection of the transmission lines for maintenance in a specific time period. Further, the tool can be easily adapted for new algorithms.
- Uncertainty in both demand and generation for transmission line maintenance in long-term horizon is yet to be accomplished.
- Integrated generation and transmission maintenance scheduling considering uncertainties have not been answered yet.

As we tried to tackle some of the gaps we observed that not all the gaps in literature can be tackled. Hence, the objective of this research is to perform economic outage scheduling of transmission line for long term horizon under different demand and wind scenarios, and proposing a customizable tool as well. The tool will facilitate in a scheduling scheme that will be able to determine the exact transmission line in the cluster of network, which can be brought out of service for maintenance. The objective problem in this study consists of a multi-objective two-stage optimization problem subjected to maintenance and network constraints. Benders decomposition approach is the chosen solution methodology and the optimization problem is solved in General Algebraic Modelling System (GAMS) environment [9]. A standardized test case is taken into consideration to provide benchmark result future reference. The general format of the mixed integer linear program adapted in benders decomposition is shown in Figure 1. The following research questions are answered at the end of this work:

- How do you aim to minimize the revenue loss of TSOs during maintenance of the transmission lines?
- What can be the suitable optimization approach to solve the maintenance problem of transmission lines for a specific period of time?
- How to address maintenance outage schedule for different demand and wind scenarios in long-term horizon?

The outline of this research is as follows: section II explains outage scheduling in long-term horizon with problem formulation and solution methodology. Section III concerns with test case and result analysis. This section explains the various data considered in this study along with the demand and wind scenarios, and later discusses the economic aspect of outage scheduling under the scenarios. Finally, section IV concludes this research work.

II. OUTAGE SCHEDULING IN LONG-TERM HORIZON

Outage scheduling problem is a multi-objective two-stage optimization problem in nature. An important aspect of problem formulation is to confirm if it is a tight mixed integer linear programming (MILP) problem or a relaxed MILP problem with relaxed constraints and assumptions. The assumptions taken into consideration for the problem formulation are described in section II.C. The primary goal is to satisfy the operating constraints for the all-plausible scenarios. The outage scheduling problem is summation of two important parameters, namely the transmission line maintenance cost and cost of lost load. All the constraints later are designed to fulfil the scheduling problem and decision variable associated with the problem. The solution provides a schedule of outages and an optimum minimized maintenance cost. All the equations and constraints corresponding to the scheduling problem are modeled GAMS environment. Selecting the maintenance horizon is important for TSOs. Since most studies focus on short-term horizon, it is difficult

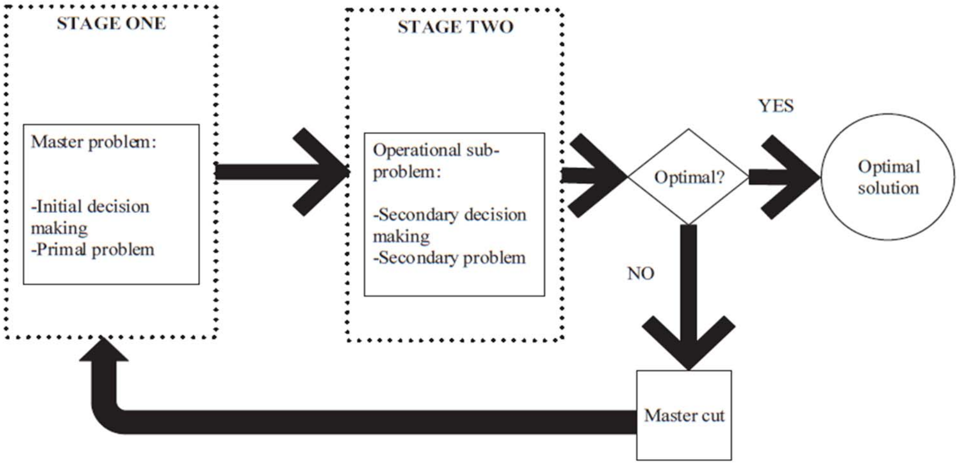

Figure 1. Benders decomposition methodology

to specify a benchmark time-scale in long-term horizon. In this study, a horizon of three months or twelve weeks is chosen as maintenance horizon.

It should be observed that performing an outage schedule for the transmission line results in the removal of a specific transmission asset, which results in loss of load and voltage imbalance that needs attention. This loss of load results in loss of revenue for the TSOs but the objective of the schedule should be performing the outage schedule in a specific time during which the loss of revenue for the transmission system operators is as minimum as possible. In this research work, the objective of the proposed approach is to perform economic outage scheduling of transmission line for long-term horizon under different demand and wind scenarios. The various demand and wind scenarios are one way of dealing future uncertainty.

A. Problem Definition

The objective function is a mixed integer linear programming (MILP) problem and its solution will provide an optimal outage schedule for the selected network. An important aspect of problem formulation is to confirm if it is a tight MILP problem or a relaxed MILP problem with relaxed constraints and assumption. The problem in this study is a relaxed MILP problem and some of the assumptions taken into consideration in this study are:

- Lossless DC power flow model is considered. As the model taken into consideration is a lossless DC power flow model, therefore the main aim of the problem formulation is to provide optimal outage schedule while satisfying the DC network security constraints.
- The scheduler has knowledge of the planned outage of the generation facility.
- Component degradation in term of failure rate and life reduction is not considered.
- The whole network is considered to be working without any failure or fault.

AC power flow model is generally considered for calculating the state of grid injection and grid flow. But the AC power flow model takes into consideration a non-linear system to describe the energy flow in transmission lines. Due to this non-linearity, AC power flow model is not opted for large network analysis. The simplified version of AC power flow model is used to perform analysis for a large network and is called DC power flow model. The advantages of using the DC power flow model are:

- The losses occurring in the grid are neglected.
- The voltage amplitude is equal for all nodes.
- The voltage angle difference between each node is very small.

Generally, maintenance scheduling is a complicated stochastic non-linear optimization problem. The scheduling is especially complicated when multiple objectives have to be optimized. The proposed approach described in this study for solving the problem formulation is a multi-objective problem, written as [10]:

$$\min Z = \sum_t \left(\sum_l C_{lt}(X_{lt}) + \sum_i (c_{it} r_{it}) \right) \tag{1}$$

where, Z is the optimized cost, C_{lt} is the transmission maintenance cost per-line and X_{lt} is the number of candidate line to be operated in right of way of transmission line l at time t, c_{it} is the loss of revenue per MW and r_{it} is the real power interruption at bus i in time t. Eq. 1 is a two-stage minimization optimization problem. The first stage determines the total maintenance cost of the selected transmission line maintenance for outage schedule and the second stage determines the total loss of revenue by the TSOs due to loss of load when the transmission line is subjected to maintenance. In this study, two types of constraints are defined, i.e., maintenance constraints and network constraints.

1) Maintenance constraints

The maintenance constraint takes into account the number of candidate lines in right of way and the maximum number of lines allowed in right of way. While deciding the candidate line, the candidate line should be available after the earliest period e_l and before the latest period l_l. The maintenance constraint can be stated as:

$$\begin{gathered} X_{lt} = 0, for\ t \leq e_l\ or\ t \geq e_l \\ X_{lt} = 0\ or\ 1, for\ e_l \leq t \leq l_l \\ \sum X_{lt} \geq (1,2,3,\dots,l), for\ t \geq e_l\ and\ t \leq l_l \end{gathered} \tag{2}$$

The above set of constraints provides the information to which transmission line is to be selected for outage from the given time window in order to obtain the minimized maintenance cost.

2) Network constrainsts

Eq. 3 represents the nodal balance equation based on the fundamental Kirchoff's law. The network constraints takes into account the voltage, power and the reliability aspect of the transmission network. The network constraints for every scenario are as follows:

$$sf + p + r = d \tag{3}$$

where, s is the node-branch incidence matrix, f is the power flow at peak load in vector form, p is the power generation by each unit at peak load in vector form, r is the real power interruption at each bus at time t in vector form and d is the load demand at every bus in vector form. Eq. 4 is the power flow through existing line in the power system:

$$f_{lt}-\gamma_l\left(\theta_i-\theta_j\right)=0 \tag{4}$$

where f_{lt} is the power flow for transmission l at time t, γ_l is the susceptance of transmission line l, and θ is the voltage angle associated to node (i,j). Eq. 5 represents the flow limits of transmission lines and generation limits of generators, written as

$$\begin{gathered}P_{l_{min}} \leq f_{lt} \leq P_{l_{max}} \\ P_{Gi_{min}} \leq P_{Gi_t} \leq P_{Gi_{max}}\end{gathered} \tag{5}$$

where, $P_{l_{max}}, P_{l_{min}}$ are the minimum and maximum power flow through transmission line l at time t, and $P_{Gi_{min}}, P_{Gi_{max}}$ are the minimum and maximum power delivered by generator at node i at time t.

B. *Convex optimization and duality*

The objective function problem is called an objective problem global variable (OPGV) [11]. This OPGV implies that the benders decomposition has objective problem subjected to a global variable. This also implies that benders decomposition also effectively deals with a convex approach towards OPGV. The OPGV has the master problem with a global variable and the sub problem with local variable. Generally, there are two types of variables, the first one being the global variable and the second one being the local variable. The global variable in the case of the problem formulation is considered in the master problem and the local variable is considered in the sub problem. The objective and constraints considered in benders decomposition are convex in the local variables. Therefore, the main reason behind solving of the problem formulation by convex approach being that the master cuts added to the master problem are generated by the means of convex duality theory.

The concept of duality plays a very important role in solving the benders decomposition technique. In principle, the concept of duality implies that every linear programming problem has dual whose objective function i.e. (for example, maximization changes to minimization). But if the primal problem has a finite optimal solution its dual after changing the objective function, there exists a finite optimal solution. Another example to explain primal and dual is that if the primal has an unfeasible solution, then, the dual should also have an unfeasible or unbounded solution. The basic transformation of primal to dual is done to reduce the number of constraints associated with the primal objective function. The transformation from primal to dual also reduces the complexity of the objective function. As the number of constraints reduce, the number of inequalities increase, which helps in solving the objective function. Increase in inequalities reduces the complexity of the linear programming problem.

C. *Relaxed constraints*

The only constraint, The only constraint which is subjected to relaxation is the cost constraint. The cost constraint takes into consideration the maintenance cost associated with transmission line during its outage condition. The maintenance cost takes into account various costs such as service cost, resource cost and component cost. As all these various costs cannot be considered in the problem formulation, we consider a single cumulative value that takes into consideration all the cost associated with maintenance of the transmission line. However, during the problem formulation, the relaxation of the maintenance cost was performed. The relaxation of the cost was done in terms of making all the maintenance cost of the transmission in the network to be same. This approach especially gave an overview as well as point of study in understanding the optimal schedule and the optimal maintenance cost of the objective function problem. Another relaxation of the constraint was done to the total transmission line that the maintenance can be performed at a specific period of time.

The maintenance cost taken into consideration for solving the test case takes into account the service cost, man power cost and various auxiliary cost. Therefore a single scalar cost for the transmission line maintenance was taken into consideration. For the result analysis involving the maintenance cost will depict the change of optimal maintenance cost before and after the cost constraint is relaxed.

D. *Methodology*

Figure 2 shows the methodology incorporated in solving the scheduling problem. The input file is imported through MS-Excel software into the GAMS and subjected to the bender decomposition algorithm to generate optimal result and schedule.

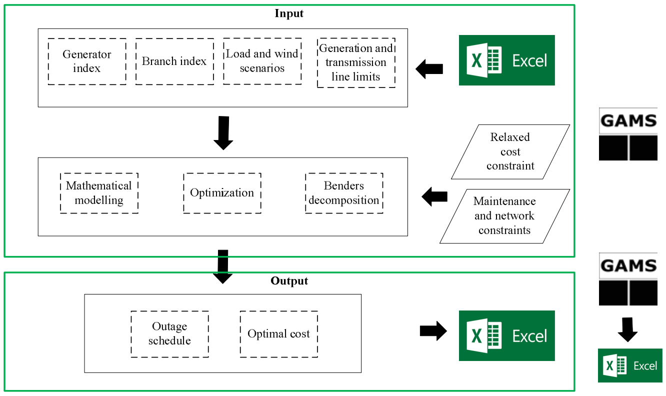

Figure 2. Work flow followed in this study

III. TEST-CASE AND RESULT ANALYSIS

A. *Input data*

The scheduling problem was validated for a modified IEEE RTS-24 bus system using GAMS. All the simulations were performed using CPLEX 12.1 running under the GAMS 23.5 environment on an Intel i5 3.9 GHz processor with 8 GB of memory. The IEEE RTS-24 bus is modified by inclusion of nine wind-farms with a total generating capacity of 3900MW, as shown in Fig. 3. It consists of 32 generators ranging from (12 to 400) MW, 24 loads, 38 transmission lines and 9 wind generation units [12].

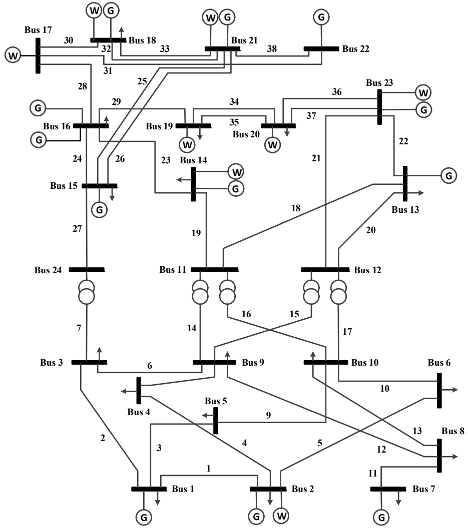

Figure 3. Updated IEEE RTS-24 bus with nine wind-farms [G: Conventional generation units, W: Wind-farms]

Two load and wind profiles are used in the study to mimic different operating conditions in the future. Figure 4 represents a base case representing current scenario and 5% increase in load growth in a year span. In addition, two wind profiles of complementary properties are used and shown in Figure 5. The use of best and worst wind days are representation of future scenarios of best and worst case.

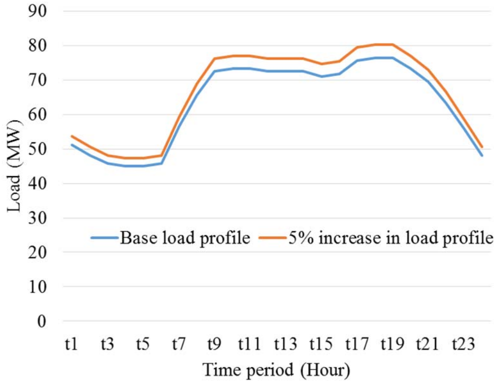

Figure 4. Load profile representing base case and a 5% increase in a year span

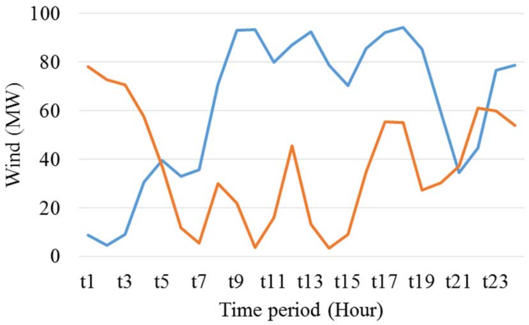

Figure 5. Wind profile representing best wind days (blue colour) and worst days (orange colour)

B. *Result and discussion*

The maintenance period chosen in this study is a span of three months. And to understand the impact of load and wind scenarios for assessing future operating condition, two different outage schedules are presented in this work. First scenario being base load and good wind days, and the second scenario being a 5% increase in load growth and worst wind days. Table I shows the outage schedule for transmission lines selected in the three month period for first scenario, and table II shows the schedule for second scenario. For each transmission line, it is assumed that the recovery time for transmission line after outage and back to normal working condition is 24 hours. The assumptions are valid under specific conditions of TSOs, such as availability of crew is always fulfilled and maintenance budgeting is properly evaluated for the considered year. From both the schedules, lines 5 and 10 (represented by L5,L10) are out of service though they supplying load at bus 6. The schedule is such that there is there is more than two months of gaps such as to perform maintenance activities and maintain supply security. A specific time-window allows TSOs to plan accordingly to meet with budget and crew requirements. The selection of lines for outage for both scenarios are different, and the time in-between maintenance of different lines allows sufficient flexibility for the TSOs to finish maintenance activities.

TABLE I. OUTAGE SCHEDULE WITH BASE LOAD PROFILE AND GOOD WIND DAYS

		Time period (days)						
Transmission lines		T11	T12	T13	..	T84	T85	T86
	L3				..	1		
	L5			1	..			
	L10				..			1
	L18		1		..			
	L23	1			..		1	

TABLE II. OUTAGE SCHEDULE WITH 5% INCREASE IN LOAD GROWTH AND WORST WIND DAYS

		Time periods (days)						
		T11	T12	T13	..	T84	T85	T86
Transmission lines	L5			1	..			
	L10				..			1
	L17				..	1		
	L18		1		..			
	L22				..		1	
	L33	1			..			

The second aspect in the scheduling problem is maintenance cost. Minimizing maintenance cost is vital for TSOs during outage scheduling. It was decided to run the outage schedule problem with different maintenance costs for a scenario with base load and good wind days. A maintenance cost of €17200/km, consisting of all auxiliary costs service costs, i.e., manpower costs and service interruption costs, is considered for the whole test case. In the second case, it was decided to divide the test case based on load point locations. For lines (1-10), the cost is €12500/km, and rest of lines is €17200/km. It was observed that the same maintenance costs pose higher costs for TSOs for the same scenario.

The third aspect is related to modeling approach and computational tractability. GAMS software tends to store all the generated equations during the iterative process. The storing of data for every iteration results in a slowdown of the algorithm convergence. If the computer hardware has limited memory, then the time taken by the algorithm to converge is high as shown in Figure 6. And, the algorithm can be optimized if the data stored during the iteration process is deleted, which is done by adding the "*option kill"* command after every iteration. As seen in Figure 6, there is a significant decrease in convergence time.

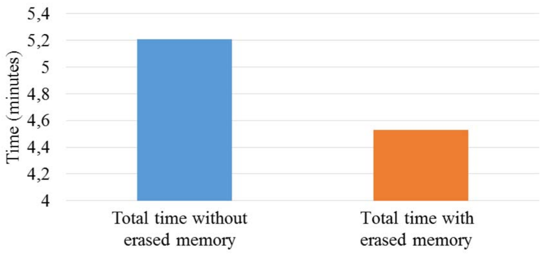

Figure 6. Convergence time based on erased memory

IV. CONCLUSION

The paper presents an outage schedule algorithm for different load and wind scenarios in a lucid manner. Foreseeing the future as scenarios breaks down the approach to a more scalable as well as tractable approach. An adaptive tool for TSOs by selecting specific part of the system, and allotting a maintenance cost for the chosen part can aim at minimize the maintenance costs. For instance, the comparison in terms of similar maintenance cost to different maintenance cost for a specific section of the network presented in this study. It can be concluded that the total maintenance cost for the selected network drops down when a section of the network has lower maintenance cost for the selected transmission lines. Therefore, a conclusion can be drawn in terms of maintenance cost stating that the TSOs have the advantage to perform the outage schedule for a specific area of the network so as to reduce the total maintenance cost. A future recommendation is to generate probabilistic scenarios for load and wind, keeping future uncertainty in mind.

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