A Two-Stage Framework for Power Transformer Asset Maintenance Management—Part I: Models and Formulations

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***Abstract*—The emergence of smart grid technologies in terms of advanced communication infrastructure, embedded intelligence, diagnostics and monitoring capabilities offers new opportunities for improved transmission asset management strategies (TAMS). Accordingly, power system operators are currently looking for analytics that can make use of transmission asset condition monitors and data already available to make better-informed decisions. This two-part paper introduces a two-stage maintenance scheduler for power transmission assets. Part I begins with the motivation for TAMS and then continues with a two-stage maintenance management model that incorporates joint midterm and short-term maintenance. The first stage involves a midterm asset maintenance scheduler that explicitly considers the asset condition dynamics in terms of failure rate. The second stage introduces a short-term maintenance scheduler with N-1 reliability that schedules the output of the midterm maintenance scheduler in the short run. The midterm and short-term stages are completely decoupled schemes to make the problem computationally tractable. For the sake of exposition here, we focus on the maintenance of grid transformers. The proposed methodology is general, however, and can be extended to other network equipments as well. The characteristics of the proposed model and its benefits are investigated in Part II through several case studies.**

***Index Terms*—Midterm and short-term maintenance planning, mixed integer linear programming, power transformers, transmission asset management.**

NOMENCLATURE

A list of nomenclature used in the paper is presented here.

A. Indices

b	Index of buses.
g	Index of generating units.
h	Index of hours.
i	Index of maintenance task or failure mode.
k	Index of transformers in midterm planning.
l	Index of transmission lines or transformers in short-term planning.
n	Index of segments in piecewise linear cost functions of generating units.
s	Index of N-1 contingency states, with $c = 0$ as the normal operating state.
sc	Index of a scenario which includes the outage of a deteriorating transformer.
t	Index of midterm maintenance time blocks.

B. Constants

$C_{\mathrm{labor}}^{\mathrm{repair}(i)}(k,t)$	Cost per working hour necessary for repairing the ith failure mode of the kth transformer in midterm time block t.
$C_{\mathrm{material}}^{\mathrm{repair}(i)}(k,t)$	Cost of materials for repairing the ith failure mode of the kth transformer in midterm time block t.
$C_{\mathrm{labor}}^{\mathrm{task}(i)}(k,t)$	Cost per working hour necessary for performing the ith maintenance task of the kth transformer in midterm time block t.
$C_{\mathrm{material}}^{\mathrm{task}(i)}(k,t)$	Cost of materials for performing the ith maintenance task on the kth transformer in midterm time block t.
d^{block}	Duration of midterm time blocks.
$d^{\mathrm{task}(i)}(k)$	Duration of the ith maintenance task for the kth transformer.
$F_l^{\max}$	Maximum capacity of transmission line or transformer l.
J_g	Shutdown cost of unit g.
K_g	Startup cost of unit g.
$K_i^0(k)$	Initial value of the ith decoupled failure rate of the kth transformer.
$K_i^j(k)$	jth stair-wise step of Weibull distribution utilized to model the ith decoupled failure rate of the kth transformer.
L_b	Number of transmission lines connected to bus b.

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$\mathrm{Labor}^{\mathrm{repair}(i)}(k)$	Number of hours necessary for repairing the ith failure mode of the kth transformer.
$\mathrm{Labor}^{\mathrm{task}(i)}(k)$	Number of hours necessary for performing the ith maintenance task of the kth transformer.
m_{sc}	Number of unavailable equipments in scenario sc.
MC_g	Minimum production cost of unit g.
$MMT(t)$	Maximum number of transformers that can be maintained in midterm time block t.
n_{sc}	Number of in service equipments in scenario sc.
NB	Number of buses.
ND	Number of decoupled failure modes or maintenance tasks.
NG	Number of generating units.
NG_b	Number of generating units connected to bus b.
Nh	Number of hours in each midterm time block.
NI_k	Number of intervals of the stair wise failure rate function of the kth transformer.
NT	Number of midterm maintenance time blocks.
NTR	Number of transformers.
NN_g	Number of segments of piecewise linear cost function of generating unit g.
NSC	Number of outage scenarios that include outage of the kth transformer.
$P_g^{\min}$	Lower limit of real power of unit g.
$P_g^{\max}$	Upper limit of real power of unit g.
P_{bh}^D	Load demand of bus b at hour h.
RU_g	Ramp-up of unit g.
RD_g	Ramp-down of unit g.
T_g^{on}	Minimum on-time of unit g.
T_g^{off}	Minimum off-time of unit g.
T	System lead time for unit commitment.
X_l	Reactance of line/transformer l.
μ_{gh}^n	Slope of segment n of the piecewise linear cost function of unit g at hour h.
τ	Spinning reserve market lead time.
$\lambda_{l_a}^c, \lambda_{l_u}^c$	Failure rates of available and unavailable equipments in scenario "sc" at the beginning of the midterm planning horizon.

C. State Variables

$C_{gh}(\cdot)$	Production cost function of unit g at hour h.
$C_{\mathrm{base}}(h)$	Operating cost at hour h when all transformers are available.
$C_{sc}(h)$	Operating cost at hour h in scenario sc.
$C^{\mathrm{task}(i)}(k,t)$	Total cost of labor and materials associated with the ith maintenance task of the kth transformer in midterm time block t.
$\mathrm{EC}^{\mathrm{failure}(i)}(k,t)$	Expected cost associated with the ith failure mode of the kth transformer in midterm time block t.
$\mathrm{EC}^{\mathrm{task}(i)}(k,t)$	Expected cost associated with the ith maintenance task of the kth transformer in midterm time block t.
$\mathrm{EC}^{\mathrm{repair}(i)}(k,t)$	Expected cost of labor and material associated with repairing the ith failure mode of kth transformer in midterm time block t.
SU_{gh}	Startup cost of unit g at hour h.
SD_{gh}	Shutdown cost of unit g at hour h.
$\pi(sc,k,t)$	Probability of scenario sc in which the kth transformer is on outage in midterm block t.

D. Decision Variables

$F_{lh,s}$	Real power flow of transmission equipment l at hour h in contingency s.
I_{gh}	Binary variable indicating the unit commitment state of unit g at hour h.
L_t	Set of transformers scheduled to be maintained in midterm time block t.
P_{gh}	Real power generation of unit g at hour h.
$P_{gh,s}$	Real power generation of unit g at hour h in contingency s.
P_{gh}^n	Real power generation of unit i in segment n at hour h.
$W_{lh}^{\mathrm{task}(i)}$	Binary variable that is equal to 1 if transformer l is under the ith maintenance task in hour h and 0 otherwise.
$X^{\mathrm{task}(i)}(k,t)$	Binary variable that is equal to 1 if the ith maintenance task is performed on the kth transformer in midterm time block t and 0 otherwise.
$Z^{\mathrm{task}(i)}(k,t)$	Continuous slack variable utilized to linearize the product of a binary and continuous variable.
X_{gh}^{on}	On time of unit g at hour h.

X_{gh}^{off}	Off time of unit g at hour h.
$\lambda(k,t)$	Failure rate of the kth transformer in midterm time block t.
$\lambda_i(k,t)$	ith decoupled failure rate of the kth transformer in midterm time block t.
$\lambda_i^{t_j}(k,t)$	ith decoupled failure rate of the kth transformer in midterm time block t when t_j periods elapsed since the last associated maintenance activity.
$\delta_{ls,h,s}$	Voltage angle of sending-end bus of line l at hour h in contingency s.
$\delta_{lr,h,s}$	Voltage angle of receiving-end bus of line l at hour h in contingency s.

I. Introduction

AGING transmission assets and dwindling utility expertise are creating an important challenge for the ongoing maintenance of the bulk electricity grid. Yet, the current deployment of smart grid technologies [a myriad of sophisticated sensors, intelligent electronic devices (IEDs) and condition monitors] is offering an unprecedented opportunity to streamline and improve transmission asset maintenance and repair strategies [1]. Transmission asset management strategies (TAMS) may be defined as strategies maximizing asset serviceability over a predefined period of time by taking into account the actual and expected asset condition dynamics, resource limitations as well as operating constraints [2].

The successful implementation of TAMS relies on four ingredients: 1) an asset data repository which provides means to gather and analyze data from all available sources such as legacy SCADA, asset condition monitors, IEDs and digital fault recorders (DFRs); 2) an analytical tool capable of extracting quantitative information about the actual and future performance of assets and their subsystems and components; 3) an effective and efficient midterm maintenance scheduler that accounts for appropriate time horizons to capture the dynamics of equipment state changes, resource limitations, reliability and transmission business drivers; and 4) an effective and efficient short-term maintenance scheduler that accounts for economics and operating constraints of the power system as well as system security in the short-run.

High-voltage transformers are among major assets making up the foundation of a transmission infrastructure. Their failure can result in high financial losses due to equipment damage and possibly environmental catastrophes, increased system operating costs and the cost of customer interruption. The increasing number of aging transformers operating close to their rating and even above it for short periods underscore the need for improved asset management strategies for transformers [3]. Accordingly, the models proposed here are applied to transformer maintenance management; however, they can be extended to encompass other transmission equipments as well.

The current state-of-the-art in transmission asset management offers at least three main approaches including time-based preventive maintenance, condition-based preventive maintenance, and reliability-centered preventive maintenance. A comprehensive literature review about transmission asset maintenance management can be found in [4]. The literature in the area of transmission equipment maintenance outage scheduling can be broadly classified into two general categories where the deciding factor is the objective function. The first category focuses on minimizing the effect of transmission equipment maintenance outage time while satisfying operating constraints, and the second category relies on maintaining or increasing the transmission equipment reliability. A comprehensive literature review regarding these approaches can be found in [5]–[10]. However, both aspects have rarely been considered simultaneously, as we are doing here.

The first part of this two-part paper introduces a two-stage maintenance scheduling methodology that incorporates midterm and short-term transformer maintenance decision-making while accounting for equipment condition dynamics. The main contribution of this part is the formulation of a two-stage transformer maintenance scheduling model which decouples the complex and combinatorial aspects of this power system planning problem. The proposed model produces successive midterm (several months ahead) and short-term (month to week ahead) coordination problems; the resulting decoupled scheduling problems are constrained to their associated time horizons where adequate levels of reliability are ensured in the midterm horizon while operating security is guaranteed in the short-term horizon. The decoupling strategy also provides the opportunity for parallel processing making the problem computationally more tractable. Additionally, the proposed model is formulated as a mixed-integer linear program (MILP) problem which facilitates its solution using available commercial solvers, e.g., [11] and [12].

The rest of this paper is organized as follows: Section II elaborates on the maintenance scheduling philosophy pursued in this paper. In Section III, the current state of the art in intelligent transformer condition monitoring and failure rate modeling is presented. A model for midterm transformer maintenance scheduling is introduced and elaborated in Section IV. Section V formulates the proposed model as an MILP. In Section VI, we link up the proposed midterm planning approach with its short-term transformer maintenance scheduler counterpart. Finally, the conclusions of the paper are presented in Section VII.

The companion paper (Part II) [13] demonstrates how the proposed framework performs on a small six-bus system and IEEE Reliability Test System (IEEE-RTS) [14]. It shows how the approach ensures mutual planning intervals' consistency in reducing operation and maintenance costs. In addition, the essential economic and computational trade-offs between the midterm and short-term horizons are uncovered in Part II [13].

II. Maintenance Planning Philosophy

Fig. 1 illustrates the proposed two-stage framework for power transformers' maintenance management. First, it is assumed that a dedicated data historian and condition-monitoring infrastructure is available within the utility. The historian collects available data sources such as legacy SCADA, asset condition monitors, IEDs and DFRs and translates them into an actual and future performance of transformers and their key components in the form of decoupled failure rate curves. Second, the midterm maintenance horizon is divided into

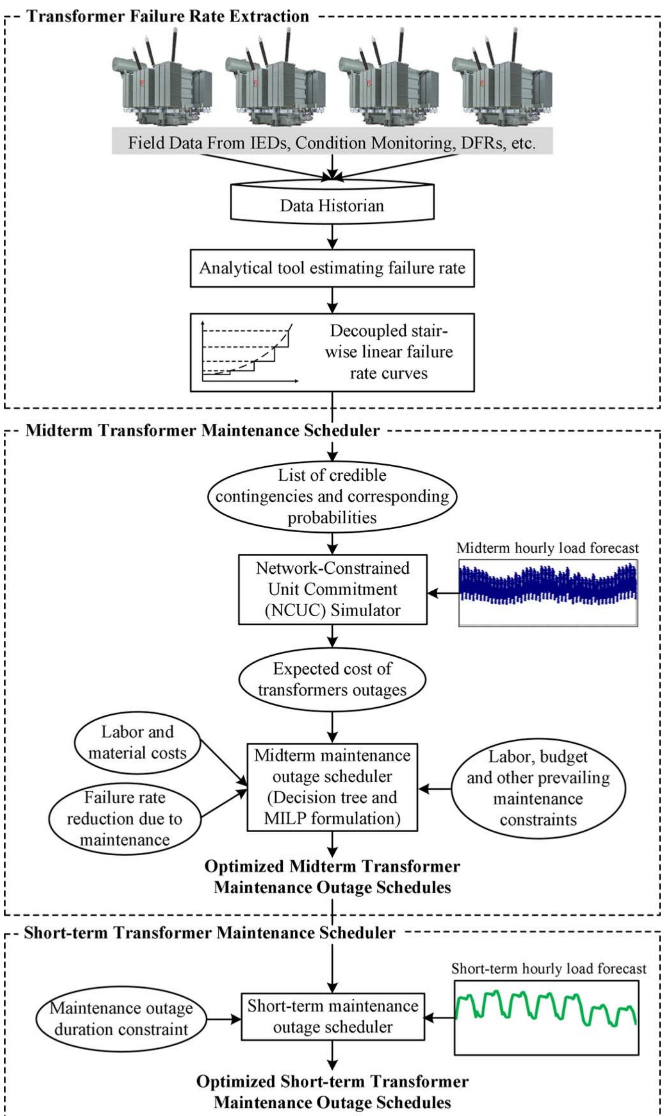

Fig. 1. Transformer maintenance management framework.

several time blocks with the same durations such as weekly or monthly time blocks. The duration of the short-term maintenance horizon equals to the duration of the midterm horizon time blocks. Then, a decision tree model is utilized to provide an effective and efficient agenda for the midterm maintenance schedules, where decisions boil down to committing to specific transformer maintenance tasks in a given midterm time block. It should be noted that the midterm maintenance model just locates the midterm time block in which the maintenance task should take place without specifying the exact outage hours of the transformer. In the midterm horizon, the impacts of failure or maintenance outages are quantified based on expected costs of outages as well as labor and material costs associated with the maintenance tasks or failure repairs. The midterm maintenance scheduler accounts for the dynamics of equipment failure rate changes, reduction in outage probabilities due to maintenance activities and finally resource limitations (primarily labor). Third, a short-term transformer maintenance scheduler is developed to determine the actual maintenance outage hours of transformers in each midterm time block considering N-1 reliability criterion and unit commitment decisions.

III. Transformer Condition Monitoring and Failure Rate Modeling Concepts

Development of analytical tools capable of extracting quantitative information about the actual and future performance of transformers as a whole and about their subsystems and components can be considered as the basis of dynamic transformer asset management strategies. Development of such tools requires a complete knowledge of transformer components, their failure mechanisms, maintenance procedures, tests, stresses such as internal temperatures, atmospheric conditions, operating circumstances such as loading histories and number of through faults, along with aging mechanisms, potential failure modes and the effect of degradation on transformer components.

Generally, aging of transformers is brought about by a combination of electrical, thermal and mechanical stresses, exacerbated by design deficiencies and insulation contamination (water, particles and so on). Power transformers' main components include the core and coil assembly, cooling systems, bushings, load tap changer, etc. The degree of transformer components' health is commonly determined based on routine tests, non-routine tests and transformer intelligent diagnostic modules based on continuous measurements [15], [16].

A. *Current State-of-the-Art in Transformer Condition Monitoring and Failure Rate Modeling*

Numerous approaches have been applied to power transformer condition monitoring and failure rate modeling. Some of these approaches use sophisticated modeling while others use simplistic rules of the thumb [17], [18]. Perhaps the most promising research results come from the Electric Power Research Institute (EPRI) [19]–[22]. EPRI initiated a significant research effort focusing on transformer sensors, condition monitors, diagnostic tools and databases in the early 1990s which matured in recent years and resulted in numerous innovations in this area.

EPRI took a big step forward to transformer fleet management in collaboration with its member utilities by establishing a transformer industry-wide database (IDB) [19]. This IDB sorts the transformers based on type, voltage class, manufacturer, and so on, which provides the capability to track transformer failure trends, and it helps to identify problems specific to a particular transformer fleet. This also allows segregation and analysis of transformers by manufacturer, model, application and risk exposure. Another stepping stone taken by EPRI is research initiated on estimating and predicting transformer failure rates [20], [21]. This work has resulted in advances in equipment failure rate modeling that can have broader application in transformer asset management. EPRI has also invented several transformer diagnostic tools such as XVisor [22]. XVisor is a rule-based power transformer expert diagnostic tool that incorporates many different tests and diagnostic activities, as well as manufacturer and vintage-specific knowledge. It turns the raw transformer test outputs into valuable information for maintenance.

All the aforementioned innovations coupled with the migration of utilities from paper-based asset archives toward asset management software communicating with up-to-date databases accessible through a variety of standards and proprietary systems lay a strong foundation for the realization of TAMS.

B. Mathematical Modeling of Transformer Failure Rate

In general, the failure of assets takes place due to the failure of one or more of its components. Thus, decoupling of failure causes based on best maintenance practices provides a more realistic overview of quantitative influence of separate factors to reliability. Mathematically, the decoupled failure probability of transformer components is quantifiable in terms of a reliability measure, i.e., failure rate, as follows [23]:

$$\lambda(k,t) = \sum_{i=1}^{ND} \lambda_i(k,t). \quad (1)$$

Although the methodology proposed in this paper is not dependent on the distribution used for failure rate modeling, the Weibull distribution is introduced here for decoupled transformer failure rate modeling, which has proven to be the most suitable distribution for this purpose [24]. Two-parameter distributions, such as Weibull, are desirable because they are inherently suited to fit any kind of data. Additionally, several well-defined methods and powerful commercial software packages exist for finding Weibull distribution parameters which would fit best to available data and equipment historical failure records. Nevertheless, any other distribution can be adopted for failure rate modeling without loss of generality as long as failure rates are constant or increasing over time. Note that the transformer failure rate modeling and condition monitoring practices are out of the scope of this paper and just briefly discussed to provide the necessary background. In the following sections, it is assumed that transformer failure rate is available in the form of a Weibull distribution or any other distribution on the provision that the expected failure rates remain constant or increase over time. In other words, it is assumed that the transformers under study are not in the infant mortality or burn-out stage [23], which is characterized by decreasing failure rate. This guarantees the convexity of the failure rate curve.

IV. Midterm Transformer Maintenance Model

The aim of the transformer midterm maintenance model is to find the optimal maintenance outage schedule based on the perceived reliability improvement through maintenance, while accounting for system economics and resource limitations. The midterm sub-problem is decoupled, modeled and solved as depicted in Fig. 1. The midterm sub-problem inputs, outputs and interactions are highlighted in the middle part of Fig. 1, which are detailed next.

Fig. 2 shows a typical Weibull distribution which is adopted to model the transformer time-varying failure rate in this paper as discussed in Section III. In the proposed model, the midterm horizon is first divided into several time blocks with the same durations such as weekly or monthly time blocks as shown in Fig. 2, e.g., $T_1, T_2, \ldots, NT$. It should be noted that in the proposed model the duration of the midterm horizon time blocks is equal to the duration of the short-term maintenance horizon. In addition, it is assumed that the maintenance tasks reduce the corresponding failure rate to its initial value or as good as new condition.

In the proposed model, the duration of midterm time blocks can be selected subjectively based on the required accuracy

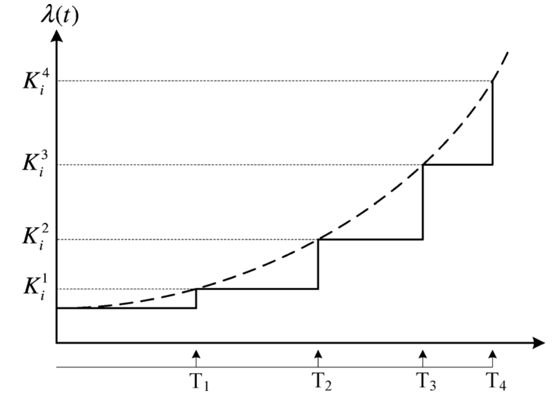

Fig. 2. Stair-wise failure rate using Weibull distribution.

and acceptable computational burden in midterm and short-term horizons. The division of the maintenance horizon into several blocks may provide significant flexibility in terms of the computation burden management and accuracy of the solutions. This has been investigated in Part II of the paper in more detail. Also, the discretization of the midterm period to several blocks makes the realization of the problem as an MILP by approximating the transformer time-varying decoupled failure rates by a stair-wise function in each block, as depicted in Fig. 2 [25].

A. Transformer Outage Consequences

In order to make prudent decisions for transformer maintenance scheduling, one should take into account the impacts of possible outages due to transformer failure as well as the impacts of maintenance outages in midterm horizon. Accordingly, transformer outage consequences in each midterm time block are quantified next.

1) Expected Cost Associated With Transformer Failure in Each Midterm Time Block: A transformer may fail at any time with a certain probability defined by its failure rate. So, the expected cost associated with transformer failure in each midterm time block may be defined as the weighted increased operation cost for each scenario sc as follows:

$$\mathrm{EC}^{\mathrm{failure}(i)}(k,t) = \sum_{sc=1}^{\mathrm{NSC}} \left[\pi_i(sc,k,t) \times \left(\sum_{h=1}^{Nh} C_{sc}(h) - \sum_{h=1}^{Nh} C_{\mathrm{base}}(h)\right)\right] \quad \forall i,k,t \quad (2)$$

$$\pi_i(sc,k,t) = \lambda_i(k,t) \times T \times \left(\prod_{l_u=1, l_u\neq k}^{m_{sc}} \left(\lambda_{l_u}^c T\right) \prod_{l_a=1}^{n_{sc}} \left(1-\lambda_{la}^c T\right)\right) \quad \forall i,k,t \quad (3)$$

where sc denotes a scenario which includes the outage of a deteriorating transformer. In each scenario, available and unavailable equipments are pre-defined which are, respectively, denoted by l_a and l_u. $\lambda_{l_a}^c$ and $\lambda_{l_u}^c$ denote the failure rates of available and unavailable equipments in scenario sc except the selected deteriorating transformer. $\lambda_{l_a}^c$ and $\lambda_{l_u}^c$ are assumed to be constant and equal to the failure rates of available and unavailable equipments in scenario sc at the beginning of the midterm planning horizon. This is while the failure rate of the selected deteriorating equipment is assumed to be time varying and denoted by $\lambda_i(k,t)$ which is characterized by a stair-wise Weibull distribution in each midterm time block. Accordingly, $\pi_i(sc,k,t)$ denotes the occurrence probability of scenario sc considering the deterioration of the ith component of the kth transformer.

The difference between $C_{\rm base}(h)$ and $C_{sc}(h)$ in (2) represents the increased operation cost due to the occurrence of scenario sc which includes the outage of a deteriorating transformer. The two cost terms $\sum_{h=1}^{Nh} C_{\rm base}(h)$ and $\sum_{h=1}^{Nh} C_{sc}(h)$ in (2) are evaluated by the network-constrained unit commitment (NCUC) simulator over the midterm period blocks using the objective function given in (4). This objective function is subject to prevailing unit commitment and DC power flow constraints. Note that, the network configuration is different while calculating $\sum_{h=1}^{Nh} C_{\rm base}(h)$ and $\sum_{h=1}^{Nh} C_{sc}(h)$; for $\sum_{h=1}^{Nh} C_{sc}(h)$, the network configuration is changed due to the occurrence of transformer failure scenario sc, while for $\sum_{h=1}^{Nh} C_{\rm base}(h)$, the network configuration is considered to be similar to the base case:

$$\min \sum_{h=1}^{Nh}\sum_{g=1}^{NG} [C_{gh}(P_{gh}, I_{gh}) + SU_{gh} + SD_{gh}]. \qquad (4)$$

It has to be noted that the proposed approach is general and any preferred technique would be utilized in (4) to calculate the operating cost, e.g., [26]–[28], on the provision that the costs are convex functions of the generators' power output. In addition, it is noteworthy that since a common practice in secure operation of power system obliges system operators to plan and operate system such that the outage of single equipment would not result in customer interruptions, the cost of customer interruptions is not taken into account in the proposed model.

2) Expected Cost Associated With Transformer Preventive Maintenance Outage in Each Midterm Time Block: The formulation proposed in (2) to model the transformer failure outage can be modified with two respects to formulate the effect of transformer preventive maintenance outage in each midterm time block as follows:

$$\begin{aligned}\mathrm{EC}^{\mathrm{task}(i)}(k,t) = &\frac{\mathrm{EC}^{\mathrm{failure}(i)}(k,t)}{(\lambda_i(k,t)\times T)} \times \frac{d^{\mathrm{task}(i)}(k)}{d^{\mathrm{block}}}\\ &-\mathrm{EC}^{\mathrm{failure}(i)}(k,t) \times \frac{d^{\mathrm{task}(i)}(k)}{d^{\mathrm{block}}}. \qquad (5)\end{aligned}$$

First, $\mathrm{EC}^{\mathrm{failure}(i)}(k,t)$ is divided by the transformer failure rate in the corresponding midterm time block since the transformer cannot fail during the maintenance. Second, $\mathrm{EC}^{\mathrm{failure}(i)}(k,t) \times (d^{\mathrm{task}(i)}(k))/(d^{\mathrm{block}})$ is subtracted from that to nullify the term $\mathrm{EC}^{\mathrm{failure}(i)}(k,t)$ in the midterm time blocks that preventive maintenance takes place for the duration of maintenance task [25]. Note that (1)–(5) quantify the costs associated with maintenance and failure outage of a deteriorating transformer in each midterm time block.

B. Labor and Material Costs

The explicit costs associated with the preventive maintenance and repair of a failed transformer include primarily labor and material costs. In general, the average number of hours and the average amount of materials required for performing preventive maintenance or repairing a failed transformer are roughly known. Thus, the labor and material costs of maintenance and repair in each midterm time block can be formulated as follows:

$$\begin{aligned}C^{\mathrm{task}(i)}(k,t) &= C_{\mathrm{labor}}^{\mathrm{task}(i)}(k,t) \times \mathrm{Labor}^{\mathrm{task}(i)}(k)\\ &\quad + C_{\mathrm{material}}^{\mathrm{task}(i)}(k,t) \qquad (6)\\ \mathrm{EC}^{\mathrm{repair}(i)}(k,t) &= \lambda_i^{\mathrm{block}}(k,t) \times \Big(C_{\mathrm{labor}}^{\mathrm{repair}(i)}(k,t)\\ &\quad \times \mathrm{Labor}^{\mathrm{repair}(i)}(k) + C_{\mathrm{material}}^{\mathrm{repair}(i)}(k,t)\Big) \qquad (7)\\ \lambda_i^{\mathrm{block}}(k,t) &= \lambda_i(k,t) \times d^{\mathrm{block}}. \qquad (8)\end{aligned}$$

The labor and material expenses in (7) are expected amounts weighted by the transformer failure rate over the midterm time block t accounting for the probabilistic nature of failures.

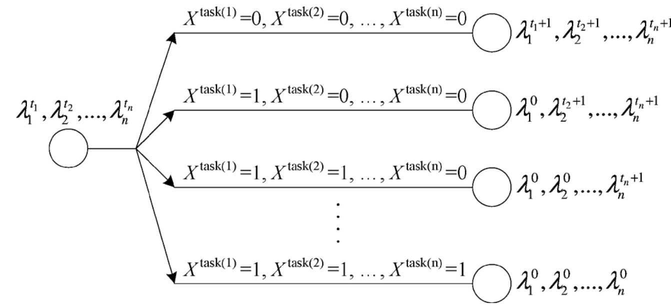

Fig. 3. Maintenance decision tree of one transformer for one period.

C. Decision Tree Model

Since the midterm time horizon is divided into several time blocks, the decision tree model can be used to provide the link between power system operations, maintenance, reliability, and the associated expected costs in different time blocks of the midterm time horizon, as illustrated in Fig. 3 [25]. The decision tree model can provide a dynamic overview of how each preventive maintenance task could affect the system cost in different midterm time blocks as the states are discriminated by failure rates, and the state transitions are based on the cost of performing or not performing maintenance in each midterm time block [29].

The number of preventive maintenance scenarios in the decision tree model for a transformer is equal to 2^N, where N represents the number of possible maintenance tasks. The transition rates between different states of this model are equal to the sum of total costs of preventive maintenance tasks performed and the expected costs that would be imposed to the system in case of transformer failure [29].

Next, the transformer midterm maintenance problem is formulated in MILP format utilizing the formulation developed in Section IV-A and B and implementing it in the decision tree model discussed in Section IV-C. In addition, an MILP formulation is presented which relates transformers' failure rates to the last maintenance activity. Note that the midterm maintenance scheduler introduced in this section just locates the midterm time block, e.g., $T_1, T_2, \ldots, NT$ in which the preventive maintenance should take place while the exact hours of maintenance outage will be determined closer to real time by the short-term maintenance scheduler (Section VI).

V. Midterm Transformer Maintenance Scheduling Problem Formulation

The mixed integer linear formulation of the proposed transformer midterm maintenance scheduling sub-problem is given in this section in (9)–(16). The objective function (9), to be minimized, is the sum of the expected costs associated with the failure and maintenance of transformers. The first two terms, $\mathrm{EC}^{\mathrm{task}(i)}$ and $C^{\mathrm{task}(i)}$, represent the costs associated with maintenance tasks in each midterm time block which are multiplied by the corresponding binary decision variable, i.e., $X^{\mathrm{task}(i)}(k,t)$. The next two terms, $\mathrm{EC}^{\mathrm{failure}(i)}$ and $\mathrm{EC}^{\mathrm{repair}(i)}$, represent the expected costs associated with the ith failure mechanism of each transformer in each midterm time block. The decision variable embedded in these terms is $\lambda_i(k,t)$ which depends on the time of the last ith maintenance of transformer k.

Constraint (10) represents the labor resource limitations. Constraint (11) enforces the impossibility of performing two pre-specified maintenance tasks on the same transformer in the same time block of the midterm period. Constraint (12) limits the maximum number of transformers that can be maintained in the same block of any midterm period. Additional constraints on the transformer maintenance scheduling can also be added to the optimization problem without loss of generality:

$$\min \sum_{t=1}^{NT}\sum_{k=1}^{NTR}\sum_{i=1}^{ND}\Big[\Big(\mathrm{EC}^{\mathrm{task}(i)}(k,t)+C^{\mathrm{task}(i)}(k,t)\Big) \times X^{\mathrm{task}(i)}(k,t)+\mathrm{EC}^{\mathrm{failure}(i)}(k,t)+\mathrm{EC}^{\mathrm{repair}(i)}(k,t)\Big] \quad (9)$$

subject to

$$\sum_{k=1}^{NTR}\sum_{i=1}^{ND}\Big[\mathrm{Labor}^{\mathrm{task}(i)}(k)\times X^{\mathrm{task}(i)}(k,t)+\lambda_i(k,t) \times \mathrm{Labor}^{\mathrm{repair}(i)}(k)\Big]\le \mathrm{Labor}(t) \quad \forall t \quad (10)$$

$$\sum_{i=1}^{ND} X^{\mathrm{task}(i)}(k,t)\le 1 \quad \forall k, \quad \forall t \quad (11)$$

$$\sum_{k=1}^{NTR}\sum_{i=1}^{ND} X^{\mathrm{task}(i)}(k,t)\le MMT(t) \quad \forall t. \quad (12)$$

The term $\mathrm{EC}^{\mathrm{task}(i)}(k,t)\times X^{\mathrm{task}(i)}(k,t)$ in the objective function contains the product of binary variable $X^{\mathrm{task}(i)}(k,t)$ and the bounded continuous variable$\lambda_i(k,t)$ embedded in $\mathrm{EC}^{\mathrm{task}(i)}(k,t)$ which makes the problem nonlinear. To remove this nonlinearity and keep the formulation as MILP, this product is substituted by a new continuous slack variable $Z^{\mathrm{task}(i)}(k,t)$ which is subjected to the following linear inequalities [30]:

$$X^{\mathrm{task}(i)}(k,t)\times\lambda_i^{\min}(k) \le Z^{\mathrm{task}(i)}(k,t)\le X^{\mathrm{task}(i)}(k,t)\times\lambda_i^{\max}(k) \quad (13)$$

$$\lambda_i(k,t)-\lambda_i^{\max}\times\Big(1-X^{\mathrm{task}(i)}(k,t)\Big) \le Z^{\mathrm{task}(i)}(k,t)\le\lambda_i(k,t)-\lambda_i^{\min} \times\Big(1-X^{task(i)}(k,t)\Big). \quad (14)$$

The last part of the proposed problem is a MILP formulation which relates transformers' failure rates to the last maintenance activity as given in (15) and (16). We refer readers to [29] for a detailed presentation of this formulation:

$$\lambda_i(k,t)\ge K_i^0(k)\times X^{\mathrm{task}(i)}(k,t) \quad (15)$$

$$\lambda_i(k,t)\ge K_i^j(k)\times\left[1-\sum_{n=0}^{j}X_i^{\mathrm{task}(i)}(k,t-n)\right] \quad \forall k=1,\ldots,NTR \quad \forall t=1,\ldots,NT \quad \forall j=0,\ldots,NI_k. \quad (16)$$

VI. Short-Term Transformer Maintenance Scheduling Problem Formulation

In this section, a short-term transformer maintenance scheduler with N-1 reliability criterion is proposed and formulated. The proposed formulation seeks to locate the exact maintenance outage hours of transformers in a given midterm time block accounting for system economics, operating constraints, as well as the N-1 reliability criterion. The inclusion of N-1 contingency constraints guarantees that the system can still tolerate the loss of any single component (generating unit or transmission component) while scheduling the transformers for maintenance. The objective function of the model, which has to be minimized, consists of energy production cost as well as startup and shutdown costs of generating units:

$$\min\sum_{h=1}^{NS}\sum_{g=1}^{NG}\left(MC_g I_{gh}+\sum_{n=1}^{NN}\mu_{gh}^n P_{gh}^n+SU_{gh}+SD_{gh}\right). \quad (17)$$

The objective function (17) is subjected to prevailing generating units' operating constraints, transmission network DC power flow constraints in normal and N-1 contingency states, as well as specific transformers' maintenance constraints, formulated as follows:

$$P_{gh,0}=P_g^{\min}I_{gh}+\sum_{n=1}^{NN_g}P_{gh}^n \quad \forall g,\ \forall h \quad (18)$$

$$0\le P_{gh}^n\le P_g^{n,\max} \quad \forall n,\ \forall g, \forall h \quad (19)$$

$$P_g^{\min}I_{gh}\xi_{g,s}^G\le P_{gh,s}\le P_g^{\max}I_{gh}\xi_{g,s}^G \quad \forall g, \forall h,\ \forall s \quad (20)$$

$$\mathrm{SU}_{gh}\ge K_g\left(I_{gh}-I_{g(h-1)}\right) \quad \forall g,\ \forall h \quad (21)$$

$$\mathrm{SD}_{gh}\ge J_g\left(I_{g(h-1)}-I_{gh}\right) \quad \forall g,\ \forall h \quad (22)$$

$$\left[X_{g(h-1)}^{\mathrm{on}}-T_g^{\mathrm{on}}\right]\left(I_{g(h-1)}-I_{gh}\right)\ge 0 \quad \forall g, \forall h \quad (23)$$

$$\left[X_{g(h-1)}^{\mathrm{off}}-T_g^{\mathrm{off}}\right]\left(I_{gh}-I_{g(h-1)}\right)\ge 0 \quad \forall g,\ \forall h \quad (24)$$

$$P_{gh,0}-P_{g(h-1),0}\le\left[1-I_{gh}\left(1-I_{g(h-1)}\right)\right]\mathrm{RU}_g + I_{gh}\left(1-I_{g(h-1)}\right)P_g^{\min} \quad \forall g,\ \forall h \quad (25)$$

$$P_{g(h-1),0}-P_{gh,0}\le[1-I_{g(h-1)}(1-I_{gh})]RD_g + I_{g(h-1)}(1-I_{gh})P_g^{\min} \quad \forall g,\ \forall h \quad (26)$$

$$P_{gh,s}-P_{gh,0}\le\mathrm{RU}_g \quad \forall g,\ \forall h,\ \forall s \quad (27)$$

$$P_{gh,0}-P_{gh,s}\le RD_g \quad \forall g,\ \forall h,\ \forall s \quad (28)$$

$$\sum_{g\in G_b}P_{gh,s}-P_{bh}^D=\sum_{l\in L_b}F_{lh,s} \quad \forall b,\ \forall h,\ \forall s \quad (29)$$

$$F_{lh,s}=\frac{1}{X_l}(\delta_{ls,h,s}-\delta_{lr,h,s}) \quad \forall l\notin L_t,\ \forall h,\ \forall s \quad (30)$$

$$F_{lh,0}=\left(1-W_{lh}^{\mathrm{task}(i)}\right)\left[\frac{1}{X_l}(\delta_{ls,h,0}-\delta_{lr,h,0})\right] \quad \forall l\in L_t,\ \forall h \quad (31)$$

$$- F_l^{\max}\xi_{l,s}^L \le F_{lh,s} \le F_l^{\max}\xi_{l,s}^L \; \forall l \notin L_t,\; \forall h,\; \forall s \quad (32)$$

$$- F_l^{\max}\left(1 - W_{lh}^{\text{task}(i)}\right) \le F_{lh,s} \le F_l^{\max}\left(1 - W_{lh}^{task(i)}\right) \forall l \in L_t,\; \forall h,\; \forall s \quad (33)$$

$$\sum_{h=1}^{NTH} W_{lh}^{\text{task}(i)} = d^{\text{task}(i)}(l) \quad \forall l \in L_t \quad (34)$$

$$\sum_{h_p=h}^{h+D_l} W_{lh_p}^{\text{task}(i)} \ge d^{\text{task}(i)}(l) \left(W_{lh}^{\text{task}(i)} - W_{l,(h-1)}^{\text{task}(i)}\right) \quad \forall l \in L_t, \forall h. \quad (35)$$

In the above formulation, the single outage of generating units and transmission components in contingency s is modeled, respectively, by vectors of binary parameters ξ_s^G and ξ_s^L. The elements of these two vectors are binary numbers, with 1 denoting the availability of components, and 0 otherwise. Once one of the units or transmission components is on outage in contingency s, the associated variable $P_{gh,s}$ or $F_{lh,s}$ would, respectively, be forced to zero by (20) or (32) [31].

The constraints (18)–(22) are the generating units' linearized energy production costs and startup and shutdown cost constraints, while (23)–(26) present the minimum on/off time and ramping up/down constraints of generating units in the normal operating state. Whenever a contingency occurs, the power production of online generating units changes such that the ramping constraints (27)–(28) and the DC power flow (29) are satisfied. Note that in the proposed model, the decision on generating units' commitment is made in normal operating state, such that only the cost of energy production in this state is entered in the objective function. In other words, assuring system integrity after any single contingency is the matter and not the cost of generation re-dispatches due to a contingency [32].

Constraints (29) are the DC power flow equations of the transmission network in the normal and contingency states. Constraints (30) represent power flow through lines and power transformers which are not considered to be scheduled for maintenance. Constraint (31) represents power flow equations for the transformers which have to be scheduled for maintenance by the model. These transformers are determined by the midterm transformer maintenance scheduler for maintenance in the midterm time block t (Sections IV and V). Constraints (32)–(33) set the transmission lines and transformers flow limits for all transmission equipments. The binary decision variable $W_{lh}^{\text{task}(i)}$ in (31) determines whether transformer l is on the ith maintenance task in hour h or not. $W_{lh}^{\text{task}(i)}$ is equal to 1 if transformer l is scheduled for the ith maintenance task in hour h, and 0 otherwise. Finally, constraints (34) and (35) enforce the continuous maintenance of transformer l for the pre-specified duration of $D_l^{\text{task}(i)}$.

Note that the constraint (31) is nonlinear as it contains the multiplication of continuous and binary decision variables. Thus, to be consistent with the MILP format of the model, it is replaced by the following linear constraints [30]:

$$W_{lh}^{\text{task}(i)} \times F_l^{\max} \le F_{lh,0}X_l - (\delta_{ls,0} - \delta_{lr,0}) \le W_{lh}^{\text{task}(i)} \times F_l^{\max} \quad \forall l, h \quad (36)$$

$$-F_l^{\max}\left(1 - W_{lh}^{task(i)}\right) \le F_{lh,0} \le F_l^{\max}\left(1 - W_{lh}^{task(i)}\right) \quad \forall l, h. \quad (37)$$

The outputs of the proposed short-term maintenance scheduler are the exact maintenance outage hours of the transformers over the scheduling horizon, the commitment status and generation level of the generating units, as well as the operating cost and locational marginal prices (LMP) at the system buses.

VII. Conclusion

A novel transformer maintenance problem formulation and solution methodology are presented in this paper in the context of midterm and short-term transmission asset maintenance scheduling. We propose a two-stage approach which maximizes the transmission asset serviceability over a predefined period of time by taking into account the actual and expected assets' condition and resource limitations in midterm horizon as well as the system economics, operating constraints and N-1 reliability in short-term horizon. The main feature of the proposed model is that it decouples the complex and combinatorial transformer maintenance scheduling problem to meaningful midterm and short-term scheduling problems, each constrained to the associated horizon constraints. The key difference between the proposed model and the existing approaches is the ability to consider the transformer condition dynamics in terms of failure rate in the midterm horizon while decoupling and solving the midterm and short-term maintenance problems in a systematic manner. The decoupling of midterm and short-term stages provides a great flexibility for midterm time block selection as well as an opportunity for parallel processing, making the problem more computationally tractable. All the formulations are developed in the mixed integer linear format which can be solved within a reasonable time by any MILP commercial solver. The proposed methodology can be extended to other transmission equipments as well.

This paper's companion [13] validates the approach on a small six-bus system and standard IEEE test system [14]. The results are such that we can claim that our proposal is technically sound, improves overall economics of transformer fleet management, and is computationally tractable on standard computing machinery.

References

[1] B. Desai and M. Lebow, "Needed: ASAP approach, intelligent fleet management for transformers: A risk-based approach," *IEEE Power & Energy Mag.*, vol. 8, no. 6, pp. 53–60, Nov./Dec. 2010.

[2] M. Shahidehpour and R. Ferrero, "Time management: Chronological strategies for power system asset management," *IEEE Power & Energy Mag.*, vol. 3, no. 3, pp. 32–38, May/Jun. 2005.

[3] W. Fu, J. D. McCalley, and V. Vittal, "Risk assessment for transformer loading," *IEEE Trans. Power Syst.*, vol. 16, no. 3, pp. 346–353, Aug. 2001.

[4] J. D. McCalley *et al.*, Automated Integration of Condition Monitoring With an Optimized Maintenance Scheduler for Circuit Breakers and Power Transformers, Final Project Report, 2006. [Online]. Available: http://www.pserc.org.

[5] Y. Fu, M. Shahidehpour, and Z. Li, "Security-constrained optimal coordination of generation and transmission maintenance outage scheduling," *IEEE Trans. Power Syst.*, vol. 22, no. 3, pp. 1302–1313, Aug. 2007.

[6] Y. Fu, Z. Li, M. Shahidehpour, T. Zheng, and E. Litvinov, "Coordination of midterm outage scheduling with short-term security-constrained unit commitment," *IEEE Trans. Power Syst.*, vol. 24, no. 4, pp. 1818–1830, Nov. 2009.

[7] L. Wu, M. Shahidehpour, and Y. Fu, "Security-constrained generation and transmission outage scheduling with uncertainties," *IEEE Trans. Power Syst.*, vol. 25, no. 3, pp. 1674–1685, Aug. 2010.

[8] Y. Jiang, Z. Zhang, J. D. McCalley, and T. Van Voorhis, "Risk-based maintenance optimization for transmission equipment," in *Proc. EPRI Subs. Equip. Diagnostics Conf.*, New Orleans, LA, Feb. 15–18, 2004.

[9] Y. Jiang, M. Ni, J. D. McCalley, and T. Van Voorhis, "Risk-based maintenance allocation and scheduling for bulk electric power transmission system equipment," in *Proc. 15th Int. Conf. Systems Engineering (ISENG 2002)*, Las Vegas, NV, Aug. 6–8, 2002.

[10] Y. Jiang, J. D. McCalley, and T. Van Voorhis, "Risk-based maintenance optimization for transmission equipment," *IEEE Trans. Power Syst.*, vol. 21, no. 3, pp. 1191–1200, Aug. 2006.

[11] "CPLEX 12 manual," IBM Corp.

[12] "The Dash XPRESS Manual," 2009. [Online]. Available: http://www.dashoptimization.com/.

[13] A. Abiri-Jahromi, M. Parvania, F. Bouffard, and M. Fotuhi-Firuzabad, "A two-stage framework for power transformer asset maintenance management—Part II: Validation results," *IEEE Trans. Power Syst.*, vol. 28, no. 2, pp. 1404–1414, May 2013.

[14] Reliability Test System Task Force, "The IEEE reliability test system—1996," *IEEE Trans. Power Syst.*, vol. 14, no. 3, pp. 1010–1020, Aug. 1999.

[15] "Facilities instructions, standards, and techniques," vol. 3–31, Transformer Diagnostics, Bureau of Reclamation Hydroelectric Research and Technical Services Group. Denver, CO, Oct. 2000.

[16] "Facilities instructions, standards, and techniques," vol. 3–31, Transformer Maintenance, Bureau of Reclamation Hydroelectric Research and Technical Services Group. Denver, CO, Jun. 2003.

[17] A. Franzén and L. Bertling, State-of-the-Art Life Time Modeling and Management of Transformers, Royal Institute of Technology, KTH School of Electrical Engineering RCAM, Aug. 2007.

[18] A. E. B. Abu-Elanien and M. M. A. Salama, "Survey on the transformer condition monitoring," in *Proc. Conf. Power Engineering*, Montreal, QC, Canada, Oct. 2007, pp. 187–191.

[19] B. Desai *et al., Transformer Performance Database: A Value Proposition for an Industry-wide Equipment Performance Database of Substation Transformers*. : EPRI, Nov. 2006.

[20] J. Bloom *et al., Information Technology for Enterprise Asset Management, An Assessment Guide*. Palo Alto, CA: EPRI, Mar. 2007.

[21] J. Bloom *et al., Substation Transformer Asset Management and Testing Methodology*. Palo Alto, CA: EPRI, Dec. 2006.

[22] B. Ward *et al., Integrated Monitoring System, Algorithms for Substation Monitoring, Dynamic Condition and Risk Assessment, System Design and Expert System Evaluation*. Palo Alto, CA: EPRI, Dec. 2005.

[23] R. Billinton and R. N. Allan, *Reliability Evaluation of Power Systems*. New York: Plenum, 1996.

[24] W. Li, *Risk Assessment of Power Systems Models, Methods and Applications*. New York: IEEE-Wiley, 2005.

[25] A. Abiri-Jahromi, M. Fotuhi-Firuzabad, and M. Parvania, "Optimized midterm preventive maintenance outage scheduling of thermal generating units," *IEEE Trans. Power Syst.*, vol. 27, no. 3, pp. 1354–1365, Aug. 2012.

[26] F. Bouffard, F. D. Galiana, and A. J. Conejo, "Market-clearing with stochastic security—Part I: Formulation," *IEEE Trans. Power Syst.*, vol. 20, no. 4, pp. 1818–1826, Nov. 2005.

[27] Y. Fu, M. Shahidehpour, and Z. Li, "Long-term security constrained unit commitment: Hybrid Dantzig-Wolfe decomposition and subgradient approach," *IEEE Trans. Power Syst.*, vol. 20, no. 4, pp. 2093–2106, Nov. 2005.

[28] L. Wu, M. Shahidehpour, and T. Li, "Stochastic security-constrained unit commitment," *IEEE Trans. Power Syst.*, vol. 22, no. 2, pp. 800–811, May 2007.

[29] A. Abiri-Jahromi, M. Fotuhi-Firuzabad, and E. Abbasi, "An efficient mixed-integer linear formulation for long-term overhead lines maintenance scheduling in power distribution systems," *IEEE Trans. Power Del.*, vol. 24, no. 4, pp. 2043–2053, Oct. 2009.

[30] C. A. Floudas, *Nonlinear and Mixed-Integer Optimization: Fundamentals and Applications*. New York: Oxford Univ. Press, 1995.

[31] M. Parvania and M. Fotuhi-Firuzabad, "Demand response scheduling by stochastic SCUC," *IEEE Trans. Smart Grid*, vol. 1, no. 1, pp. 89–98, Jun. 2010.

[32] K. W. Hedman, R. P. O'Neill, E. B. Fisher, and S. S. Oren, "Optimal transmission switching with contingency analysis," *IEEE Trans. Power Syst.*, vol. 24, no. 3, pp. 1577–1586, Aug. 2009.

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