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The Effect of Condition Monitoring of Circuit Breaker on the Reliability and Maintenance Cost of Substation

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ABSTRACT

Over the recent years, a number of new maintenances methods for high voltage substations have been introduced to reduce the number of substation events. The primary purpose of the present study is to presents a Cost-benefit analysis for Circuit Breakers (CBs) in a substation equipped with Condition Monitoring (CM) devices. To this end, a mathematical formulation to categorize and model equipment failures based on their severity is developed. By CM, some of severity failures, named major failures, can be detected early, and corrected as the minor failure. This formulation quantifies the effect of CM devices on the outage rate and Predictive Maintenance (PDM) rate of the equipment. The PDM rate is used to modify the Markov maintenance model for the equipment. The proposed modified Markov model quantifies the effect of CM on the maintenance costs and lifetime of CB. The New Markov model is compared with the Preventive Maintenance (PM) model. Expected Energy Not Supply (EENS) and reliability Cost are calculated with and without CM on CBs. Finally, the proposed model is applied on the CBs of 400/132/20KV substation in the Khorasan Regional Electricity Company (KREC) in Iran. The obtained results show that CM on CBs of substations improves the EENS and reliability cost by 82.43 %. Moreover, the maintenance cost of the proposed model shows an improvement of 9.07 % compared to PM model. Finally, the total annual costs show an improvement of 80.67% due to CM on CBs.

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I. Introduction

A. Previous works

Recently CM systems used to monitor the health condition of the equipment have been wildly implemented in power substations [1-5]. The reliability of the single network element equipped with a Prognostics and Health Management (PHM) system is estimated in [1]. Then, this reference applies genetic algorithms for optimal allocation of PHM systems considering the cost and reliability of the network. [2] corrects the failure and repair rates of power components equipped with smart monitoring systems using a multiple-state Markov chain model and [3] proposes an analytic, time-variant model to evaluate the reliability improvement of a component that is equipped with a PHM system. [4] Proposes a new mixed-integer optimization model for generation maintenance scheduling, which effectively incorporate the dynamic information about the health and maintenance cost of generators, provided by the Bayesian prognostic models. [5] Proposes a framework that extends the maintenance model presented herein, and consider the effects of maintenance on network operation by coordinating generator maintenance schedules with the unit commitment and dispatch decisions. This reference introduces new reformulations and efficient algorithms for solving

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large-scale instances of the proposed maintenance-scheduling model. Extensive computational studies using real-world degradation data demonstrates the effectiveness of the new framework.

The reliability studies of the network are highly affected. One of the key elements of the substation is CB through equipping the elements of the substations with CM. CBs failures accounts for about 39% of substation failures [6]. Therefore, CM of CBs can improve the reliability of the substation while decreasing both annual reliability and maintenance costs. The Organization of the maintenance process of system components based on the reliability of the system is named Reliability-centered maintenance (RCM), which discussed comprehensively in [7] and [8]. Determining the optimal maintenance strategy of an electric power supply as a realistic complex system respecting a given reliability constraint is discussed in [9]. Research on Condition-Based Maintenance (CBM) has been increasing rapidly due to the development of the monitoring technologies. The proper design of CBM can be effective in improving the reliability of equipment [10-11]. A review of CBM research studies is presented in [11]. [12] Represents two main challenges in strategies for periodical maintenance. First, many actual engineering systems have complex characteristics and so the fixed inspection strategies are not suitable decisions. Second, by increasing the operation time of equipment, a fixed interval inspection is not tailored in practice. Therefore, this reference proposes a mixed time/condition-based probabilistic maintenance model. In [13], Different maintenance approaches are implemented on a mechanical component to understand their benefits, concluding that, in general, the advanced CBM and PreDictive Maintenance (PDM) policies are associated with a relatively better performance. However, there are a number of situations in which the PM shows a better performance. [14] Shows that the maintenance policies that use the real-time monitoring technologies improve the performance of manufacturing systems. This reference proposes the integration of intelligent sensor networks to monitor the equipment in its predictive maintenance activity. [15] Proposes a Maintenance strategy for the overhead lines based on condition monitoring and the reliability of the network. For this purpose, it quantifies the relationship between the condition monitoring data and the failure rate of overhead lines. Then the EENS index is calculated using the new failure rates of overhead lines.

As mentioned in the literature, the use of CM devices does not mean that the PM is not required. However, a comprehensive model to evaluate the combined preventive and predictive maintenance is not presented in previous research studies. The effect of CM devices on the failure rate of the equipment has been investigated but the effect of CM devices on the PDM rate of the equipment has not been investigated.

B. Contribution

In this paper, a Cost-benefit analysis is proposed for CB in a substation to be equipped with CM devices. For this, a mathematical-simulation procedure is extended in four steps in this paper as shown in Fig. 1.

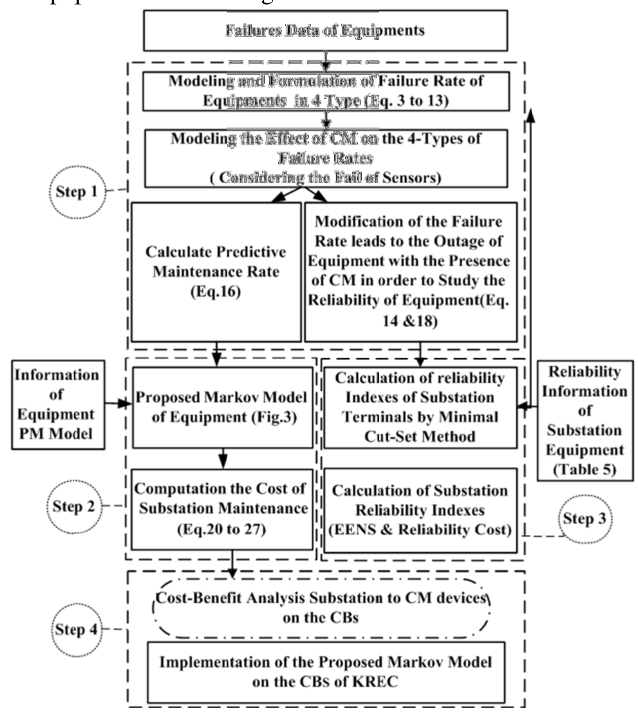

Fig.1. flowchart of Substations Cost-benefit analysis for CM

Step1: The main innovation of the first step is to provide a mathematical formulation to categorize and model the failures of the equipment based on its severity. CM employs information from multiple sensors. The Probability of failure of smart sensors has been taken into account. In fact, by CM, some of the severity failures, named major failures, can early be detected and corrected as the minor failures. The proposed mathematical formulation quantifies the effect of CM on the outage rate and PDM rate of the equipment. The PDM rate is used in step 2 as the smart inspection rate of the equipment. The outage rate is used in step 3 to study the reliability of the equipment in the presence of CM devices in the network.

Step2: By CM, smart inspections are added to the previous Markov model in [7]. Smart inspections detect and correct failures in the non-scheduled minor and major maintenances. In the second step, at first, a new integrated preventive and predictive maintenance Markov model is proposed to study the effect of the CM on the maintenance process and its associated costs. The PDM rate, obtained at the first step, is used as the smart inspection rate at modified Markov model.

Step3: In order to consider the failures of equipment of substation on the reliability, the station oriented reliability evaluation techniques are used [16]. Improving the failure rate of CBs by CM improves the reliability of the network. To quantify this improvement, at first, using the minimal cut set method, the reliability indices of substation are calculated in two states: with and without CM of CB. Then, EENS of the substation and reliability costs are calculated.

Step4: The fourth step a Cost-benefit analysis substation to install CM devices on the CBs in the viewpoint of the annual total cost. The annual total cost includes maintenance cost reliability cost and installation cost of CM devices. Finally, the proposed model is applied on the CBs in power transmission network in the Khorasan Regional Electricity Company (KREC) in Iran.

The novelties of the paper that do not exist in other References are as follows:

1. Presentation of new mathematical model of equipment failures (Section 3):

1.1. Proposing innovative mathematical model to categorize the types of equipment failures and determine the failure rates.

1.2. Developing the proposed mathematical model to calculate the effect of sensor installation on the failure rates of equipments. Moreover predictive maintenance rate is introduced in this section.

1.3. The failure probabilities of sensors are also modeled.

2. Presentation a new integrated preventive and predictive maintenance Markov model to analyze the effect of the CM on the maintenance process and its associated costs (Section 4).

3. Cost-worth Analysis of proposed method by considering the sensor installation costs, reliability cost and maintenance cost (Section 5).

4. Applying the proposed method on the 132KV and 400KV CBs of KREC with a comprehensive statistical study (Section6).

C. Article structure

In the second section, the statement of the problem including evaluation of substation reliability is addressed. The third section focuses on the analytical modeling of CM on the failure rate. In section four, a new integrated preventive and predictive maintenance Markov model is proposed. Cos-worth analysis is presented in section five. The six section reviews the case studies. Finally, the section seven summarizes drawn conclusion.

II. STATEMENT OF THE PROBLEM

Smart network monitoring performs preventive operations to maintain network reliability. When a failure occurs in some part of the power network, smart monitoring with preventive operations can help detect failures, reduce the repair time, and increase repair rates [2].

A. Evaluation of substation reliability

The minimal cut-set method is the conventional method for evaluating substation reliability. A cut-set is a set of system elements whose failures cause system failure. A cut- set is said to be a minimal if, when any of its elements has remained, the system remains properly. To evaluate the substation reliability, the minimal cut-sets of all terminals, which lead to the loss of them, are calculated. Then, using parallel and series methods as presented below and with partial approximation, the reliability indices of each terminal are calculated. The elements of minimal cut-set are parallel to each other in terms of reliability diagram. In this sense, the loss of all of them leads to the loss of the terminal; however, the presence of one of them leads to the continuity of the terminal's power supply. Therefore, the reliability of each cut-set depends on the reliability of the parallel equipment. Equ. (1), shows the reliability of the system consisting of two parallel devices with failure rates of λ_1 and λ_2 and repair times r_1 and r_2 [17].

$$\lambda_{pa} = \frac{\lambda_1 \lambda_2 (r_1 + r_2)}{1 + \lambda_1 r_1 + \lambda_2 r_2}, r_{pa} = \frac{r_1 r_2}{r_1 + r_2} \quad (1)$$

Where λ_{pa} is the parallel system failure rate and r_{pa} is the parallel repair time. All cut-sets of each terminal are in series from the perspective of reliability diagram. Therefore, the reliability of each terminal is obtained based on the reliability of the series elements in accordance with Equ. (2).

$$\lambda_s = \sum_i \lambda_i, U_s = \sum_i \lambda_i r_i, r_s = \frac{U_s}{\lambda_s} \quad (2)$$

Where λ_s is the failure rate of the system series, r_s is the repair time of the series system and U_s is the mean annual outage time [17].

In this paper Reliability Calculation of Power System (RCOPS) program, which is developed by the authors in MatLab-language M-files, is used to evaluate the reliability of the power system. RCOPS program examines the reliability of substations with the help of the minimal cut-set. Fig.2 shows the flowchart of sub-program of RCOPS that calculates the reliability of substation.

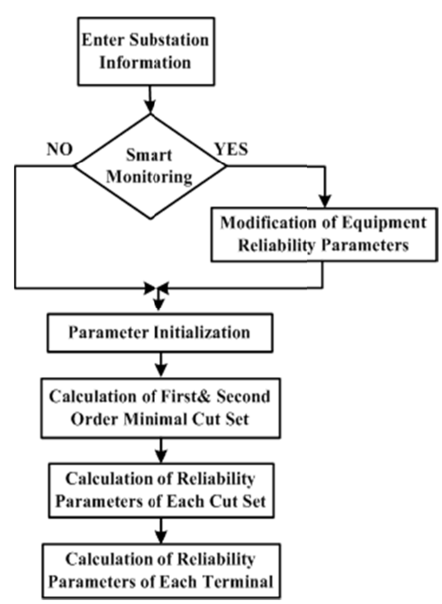

Fig.2. the process of calculating the reliability of each substation in RCOPS

III. Analytical Modeling of Equipment Failures with CM

For the analytical modeling of the effect of CM on equipment reliability, it is necessary to model the failure factors along with their failure frequency in the equipment. Equ. (3), shows the set of failures of equipment A, which includes X type of failure:

$$A=\{A_x\}, \quad x=1,...,X \tag{3}$$

Where A_x is the failure type x of equipment A.

The total number of failures for N equipment of type A, in the study period of T, is in accordance with Equ. (4):

$$n_A=\{n_x\}, \quad x=1,...,X \tag{4}$$

In Equ. (5), the general relation of the failure rate of equipment A is expressed based on the failure type x:

$$\lambda_x=\frac{n_x}{N.T} \tag{5}$$

In this paper, failures are divided into four categories, based on their severities:

1) The failure x does not create a problem for the system; In fact, there is a minor failure; Therefore, it can remain until its maintenance and correction in scheduled outage. In this case, the failure rate of equipment A, which can be corrected in scheduled outage, is defined in accordance with Equ. (6):

$$\lambda_M = \sum_{x=1}^{X} \lambda_x M_x \tag{6}$$

Which:

$$M_x=\begin{cases}1 & \text{Failure } x \text{ will be } \textit{corrected in scheduled outage}\\ 0 & \textit{Other}\end{cases} \tag{7}$$

2) The failure x can be corrected in on-loaded repair, with no need to outage the equipment; In fact, there is a minor failure; In this case, the failure rate of equipment A, which is corrected in on-loaded repair, is defined in accordance with Equ. (8):

$$\lambda_p = \sum_{x=1}^{X} \lambda_x P_x \tag{8}$$

Which:

$$P_x=\begin{cases}1 & \text{Failure } x \text{ can be corrected in on-loaded repair}\\ 0 & \textit{Other}\end{cases} \tag{9}$$

3) The failure x is important, requiring immediate action by the repair team and emergency outage of equipment A. In fact, there is a minor failure; the failure rate of equipment A, which is corrected by emergency outage of repair team is:

$$\lambda_E = \sum_{x=1}^{X} \lambda_x E_x \tag{10}$$

Which:

$$E_x=\begin{cases}1 & \text{Failure x requires an emergency outage}\\ 0 & \textit{Other}\end{cases} \tag{11}$$

4) The failure x cause trip of equipment A. In fact, there is a major failure; this type of failures constructs the outage rate of equipment in Equ. (12):

$$\lambda_T = \sum_{x=1}^{X} \lambda_x T_x \tag{12}$$

Which:

$$T_x=\begin{cases}1 & \text{Failure } x \text{ causes equipment outage}\\ 0 & \textit{Other}\end{cases} \tag{13}$$

The CM reduces the outage rate. If the failure of x is of the fourth type (T_x= 1) detected by the CM devices (S_x= 1), then the failure of type x will not cause equipment outage and will be deducted from the fourth type failure rate. Since the CM devices cannot detect all of the fourth-type failures, the outage rate does not reach zero. With these definitions, Equ. (14), defines the outage rate of equipment A when the CM devices detect the failures.

$$\lambda_{Tnew} = \sum_{x=1}^{X} \lambda_x (T_x - S_x T_x) \tag{14}$$

Which:

$$S_x=\begin{cases}1 & \text{Failure } x \text{ is detected by } \textit{CM devices}\\ 0 & \textit{Other}\end{cases} \tag{15}$$

Certainly, early detection of failure type x through CM, adds this failure in accordance with Equ. (16) to the second or third failure type and will be corrected by action taken by the repair team in predictive repair. In Equ. (16), λ_{PDM} is the PDM rate:

$$\lambda_{PDM} = \sum_{x=1}^{X} \lambda_x (P_x + E_x + S_x T_x) \tag{16}$$

Where we always have:

$$E_x + P_x + M_x + T_x = 1 \tag{17}$$

By using the conditional probability method, the outage rate of equipment A in Equ. (19) can be modified in Equ. (18) considering the probability of failure of CM devices:

$$\lambda_{Tnew\bullet} = \lambda_{Tnew}\left(\prod_{s=1}^{S} P_s\right) + \sum_{m=1}^{S}\left(\lambda_m\left(\prod_{s\neq m} P_s\right)Q_m\right) + \sum_n\sum_m\left(\lambda_{n,m}\left(\prod_{s\neq n,m} P_s\right)Q_n Q_m\right)+\ldots \tag{18}$$

Where λ_m is the outage rate A, assuming the proper function of all CM devices except CM device m. $\lambda_{n,m}$ is also the equipment outage rate, assuming proper function of CM devices except CM devices n and m. In this study, it is assumed that the probability of simultaneous failure of two CM devices and more is zero. The PDM rate in Equ. (16) can be corrected similarly. By CM devices according to Equ. (14) and (18), the equipment failure rate changes to $\lambda_{Tnew}\bullet$. Surely reducing the failure rate of equipment by CM will reduce reliability Cost .The cost of loss of load, which is known as reliability cost, calculate in Equ. (19).

$$C_{Reliability\ Cost} = EENS \times VOLL \tag{19}$$

In which VOLL is the Value Of Lost of Load.

IV. Proposing a New Maintenance Markov Model

CM adds smart inspections to the previous Markov model in [7]. Smart inspections detect and correct failures in the minor and major maintenance of non-scheduled. Therefore, the frequency of going to major maintenance in PM is reduced. In the other words, by CM, the PDM can be added to the PM, and is named as integrated predictive and preventive maintenance model. If, in accordance with [7], the aging process of equipment is considered in three modes, Fig.3 shows the presented Markov model in this paper. In the presented Markov model, PM include periodic inspections, periodic minor maintenances and periodic major maintenances. On the other hand, PDM involves inspections based on need, minor maintenance based on need, and major maintenance based on need. The states that are marked with dotted lines, model the PDM, which is added to previous PM Markov model. In Fig.3, I'_2 and I'_3 are smart inspection status in the proposed Markov model. γ'_1, γ'_2 and γ'_3 are the smart inspection rates for equipment in the proposed Markov model. Smart inspection rates are the same as the failure rate detected by CM devices with the possibility of CM devices failure ($\lambda^{\bullet}_{PDM}$). The M' and MM' states, show the minor and major maintenance of non-scheduled respectively. It is expected that the frequency occurrence of state F in the proposed Markov model is less than PM model, which means that by CM, equipment needs to be replaced later and the lifetime of the equipment will increase. On the other hand, it is expected the frequency occurrence of major maintenance, in the presence of CM, to be reduced compared to the condition without CM; in fact, the equipment failures are detected in minor states and corrected in minor maintenances.

V. COSTS-WORTH ANALYSIS OF THE PROPOSED MODEL

The annual costs of the proposed Markov model includes the inspection cost, the minor maintenance cost, the major maintenance cost, and the cost of replacing the equipment in a steady state (F status) which are shown in Equs. (20)-(23), respectively. The corrective repair cost due to trip of equipment is shown in Equ. (24).

$$C^{Inspection} = C^{I}\left(\sum_{i=1}^{3} f_{I_i} + \sum_{i=2}^{3} f_{I'_i}\right) \tag{20}$$

$$C^{Minor\ Maintenance} = C^{M}\left(\sum_{i=1}^{3} f_{M_i} + \sum_{i=2}^{3} f_{M'_i}\right) \tag{21}$$

$$C^{Major\ Maintenance} = C^{MM}\left(\sum_{i=1}^{3} f_{MM_i} + \sum_{i=2}^{3} f_{MM'_i}\right) \tag{22}$$

$$C^{Replacement} = C^{R} F_F \tag{23}$$

$$C^{Repair} = C^{MM} \lambda_f \tag{24}$$

C^I, C^M, C^{MM} and C^R are the mean cost per inspection activity, minor maintenance, major maintenance and equipment replacement, respectively. Furthermore, f_{I_i}, f_{M_i}, f_{MM_i} and F_F are the frequency occurrence of the inspection, minor maintenance, major maintenance and equipment replacement, respectively. C^{Repair} is the cost of corrective repair. In Equ. (25) According to the type of maintenance, the λ_f is:

$$\lambda_f = \begin{cases} \lambda_T & PM \\ \lambda_{T_{new}^{\bullet}} & proposed\ Model \end{cases} \tag{25}$$

Equ. (26), indicates the annual maintenance costs of the proposed Markov Model. The frequency occurrence of PDM states is zero, if only the PM model is applied.

$$\begin{aligned} C^{Maintenance}_{Proposed\ Model} &= C^{I}\left(\sum_{i=1}^{3} f_{I_i} + \sum_{i=2}^{3} f_{I'_i}\right) + C^{M}\left(\sum_{i=1}^{3} f_{M_i} + \sum_{i=2}^{3} f_{M'_i}\right) \\ &+ C^{MM}\left(\sum_{i=1}^{3} f_{MM_i} + \sum_{i=2}^{3} f_{MM'_i}\right) + C^{R} F_F \end{aligned} \tag{26}$$

In (27) the cost of CM devices on the CBs is considered.

$$C_{Total} = C_{\text{Maintenance}} + C_{\text{Reliability Cost}} + C_{\text{CM devices}} + C^{MM} \lambda_f \tag{27}$$

VI. CASE STUDIES

In this section, the proposed approach is applied on the CBs of the KREC in Iran to verify the effectiveness and applicability of the method.

A. Statistical study of KREC Failures

In this section, the failures of CBs in the KREC in Iran, and the effect of applying CM on them have been studied. To do so, a statistical study was performed on the failure data of all CBs of KREC. The study was conducted during 4 years, from 2014 to 2017. Table I and Table II indicate the failure types of CBs 400KV and 132KV in KREC, respectively. The values M_X, P_X, E_X, T_X and S_X in these tables are determined in accordance with Equs. (7), (9), (11), (13) and (15), respectively. In addition, based on the Equs. (6), (8), (10), and (12), the four type failure rates of CBs are calculated.

TABLE I
THE SET OF FAILURES OCCURRED IN CBS 400KV OF KREC

Failure Factor	A_x	Nu/(4Yr)	Failure Rate	M_x	P_x	E_x	T_x	S_x
SF6 gas pressure low	A_1	4	0.0101	0	0	0	1	1
Indicator	A_2	1	0.0025	0	0	1	0	0
Mechanical interlock	A_3	1	0.0025	0	0	0	1	0
Door panel	A_4	3	0.0076	0	1	0	0	0
Heater	A_5	1	0.0025	0	1	0	0	0
Numerator	A_6	5	0.0126	1	0	0	0	0
Disconnect or connect coil	A_7	2	0.0051	0	0	0	1	0
	A_8	1	0.0025	0	0	1	0	0
Spring charging mechanism	A_9	1	0.0025	0	0	0	1	0
Not regularization	A_{10}	1	0.0025	0	0	0	1	0
Sf6 gas leakage	A_{11}	1	0.0025	0	0	0	1	1
Heavy leakage of oil	A_{12}	2	0.0051	0	0	0	1	1
	A_{13}	1	0.0025	0	0	1	0	1

TABLE II
THE SET OF FAILURES OCCURRED IN CBS 132KV OF KREC

Failure Factor	A_x	Nu/(4Yr)	Rate Failure	M_x	P_x	E_x	T_x	S_x
SF6 gas pressure low	A_1	31	0.016454	0	0	0	1	1
	A_2	10	0.005308	0	0	1	0	1
	A_3	5	0.002654	1	0	0	0	1
Hydraulic oil leakage	A_4	7	0.003715	0	0	0	1	1
	A_5	1	0.000531	0	0	1	0	1
	A_6	1	0.000531	1	0	0	0	1
Indicator	A_7	2	0.001062	1	0	0	0	0
Door panel	A_8	1	0.000531	0	1	0	0	0
Heater	A_9	1	0.000531	0	1	0	0	0
	A_{10}	1	0.000531	1	0	0	0	0
Numerator	A_{11}	5	0.002654	0	1	0	0	0
	A_{12}	3	0.001592	1	0	0	0	0
Disconnect or connect coil	A_{13}	2	0.001062	0	0	0	1	0
Spring charging mechanism	A_{14}	3	0.001592	0	0	0	1	0
	A_{15}	3	0.001592	0	1	0	0	0
Sf6 gas leakage	A_{16}	2	0.001062	0	0	0	1	1
Manual command	A_{17}	2	0.001062	0	1	0	0	0
Panel micro switches	A_{18}	2	0.001062	1	0	0	0	0
Contactor	A_{19}	4	0.002123	0	0	0	1	0
	A_{20}	2	0.001062	0	1	0	0	0
Loose of connections	A_{21}	1	0.000531	0	0	1	0	0
False signal	A_{22}	1	0.000531	1	0	0	0	0
Arched and defective insulators	A_{23}	2	0.001062	0	0	0	1	1
Heavy leakage of oil	A_{24}	17	0.009023	0	0	0	1	1
	A_{25}	7	0.003715	0	1	0	0	1
	A_{26}	4	0.002123	1	0	0	0	1
Other	A_{27}	2	0.001062	1	0	0	0	0

B. Calculating the Equipment Failure Rate

In this paper, it is assumed that three sensors S_1, acoustic emission sensor, S_2 pressure sensor, and S_3, radiation sensor are installed for CM of CB. Table III shows different types of CM devices and set of failure factors that are detected by CM. λ_T in Table IV indicates the outage rate of CB without CM, calculated by Equ. (12). If the failure probability of sensor is considered as 0.001, λ_{Tnew} and λ_{PDM} show the outage rate and predictive maintenance rate of CB without considering the sensor failure probability, according to Equs. (14) and (16). $\lambda_{Tnew\bullet}$ and $\lambda_{PDM\bullet}$ show the outage rate and predictive maintenance rate of CB with considering sensor failure probability, according to Equ. (18). The outage rate of the CBs 400KV and 132kv decreases from 0.030303(f/yr) to 0.012661(f/yr) and 0.036093(f/yr) to 0.004808(f/yr) by CM, respectively. The PDM rate is 0.035318(f/yr) and 0.048801(f/yr) respectively. It must be noted that by considering the failure probability of sensors, the outage rate is increased while the PDM rate is decreased.

TABLE III
THE SET OF FACTORS FAILURE DETECTED BY SENSORS

CB	CM devices (sensors)	set of failures factors detected by sensors
400KV	S_3	A_1 , A_{12}, A_{13}
	S_1	A_{11}
132KV	S_1	A_4 , A_5, A_6, A_{16}
	S_2	A_{23}
	S_3	A_1 , A_2, A_3, A_{24}, A_{25}, A_{26}

TABLE IV
CB FAILURE RATES WITH PROBABILITY OF FAILURE OF SENSORS

CB	λ_T	λ_{Tnew}	λ_{PDM}	$\lambda_{Tnew\bullet}$	$\lambda_{PDM\bullet}$
400KV	0.030303	0.012626	0.035354	0.012661	0.035318
132KV	0.036093	0.004777	0.048832	0.004808	0.048801

C. Calculation of the reliability cost of substation

Fig.4 shows a substation 400/132/20KV in KREC, which consists of three sections 400KV, 132KV and 20KV. The 400KV section is a one-and-a-half breaker scheme with nine CB, four output terminals, and two bus bars 400KV, feeding two transformers 200MVA. The 132KV section is an H-scheme with 11 CB, 8 terminals and 2 bus bars of 132KV which connected by bus coupler CB_{11}. The 20KV section is used as an internal consumer.

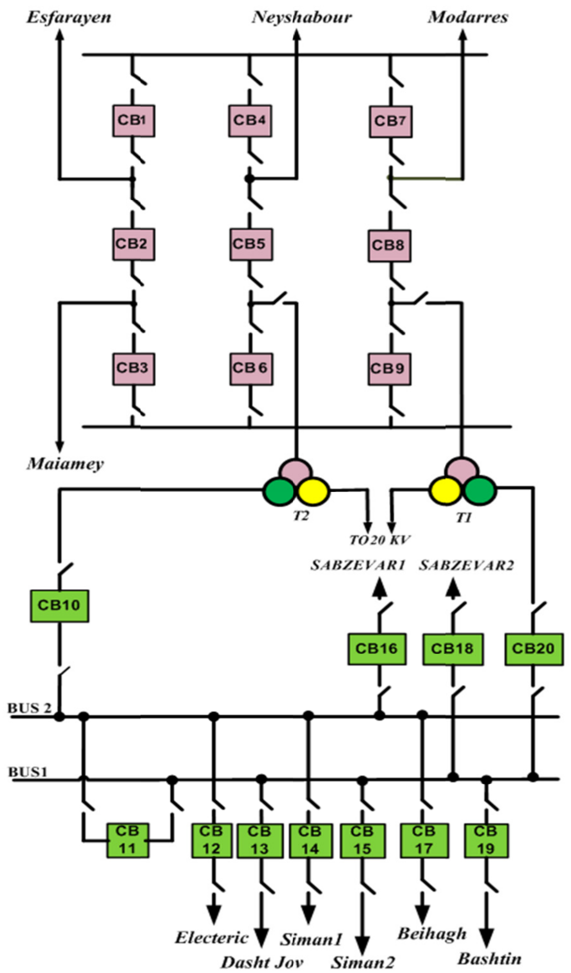

Fig.4. Sample substation of KREC

Table V presents the reliability parameters of substation 400/132/20KV. Table VI shows the failure rate, λ, average repair time, *R*, average annual outage time, *U*, and the probability of loss of terminals of substation, in two status of without CM and with CM of CB. These parameters are calculated implementing minimal cut-set method. The EENS and reliability cost of each terminal are calculated in Table VII. The EENS and reliability cost of each terminal with and without CM on CBs are shown in fig. 5 and fig. 6.

TABLE V
RELIABILITY INFORMATION OF SUBSTATION EQUIPMENT

Equipment	Active Failure rate (F/yr)	Passive failure rate (F/yr)	Total failure rate (F/yr)	Repair time (Hr)
CB(400KV)	0.0066	0.0303	0.0369	20
CB(132KV)	0.0098	0.0360	0.0458	64
Bus Bar (400kv)	-	-	0.0064	8
Bus Bar (132KV)	-	-	0.0031	15
Transformer	-	-	0.32	40

TABLE VI
RELIABILITY INDICES OF ONE-AND-A-HALF BREAKER SCHEME OF 400 KV SUBSTATION IN KREC

	Terminal	λ	*R*	*U*	Probability
Without smart sensors	Esfarayen	0.03783	6.995116	0.264628	0.0000302
	Maiamey	0.03783	6.995116	0.264628	0.0000302
	Neyshabour	0.044962	6.042845	0.271701	0.0000310
	Modarres	0.04443	6.10456	0.271228	0.0000310
	Electeric	0.408983	21.9078	8.959909	0.001022
	Dasht Jov	0.408983	21.9078	8.959909	0.001022
	Siman1	0.408983	21.9078	8.959909	0.001022
	Siman 2	0.408983	21.9078	8.96E+00	0.001022
	Sabzevar1	0.408983	21.9078	8.959909	0.001022
	Beihagh	0.408983	21.9078	8.959909	0.001022
	Sabzevar2	0.408983	21.9078	8.959909	0.001022
	Bashtin	0.408516	21.89733	8.945411	0.00102
With smart sensors	Esfarayen	0.022408	5.515034	0.123581	0.0000141
	Maiamey	0.022408	5.515034	0.123581	0.0000141
	Neyshabour	0.02954	4.422942	0.130654	0.0000149
	Modarres	0.029008	4.487759	0.130181	0.00015
	Electeric	0.068503	19.17674	1.313662	0.00015
	Dasht Jov	0.068503	19.17674	1.313662	0.00015
	Siman1	0.068503	19.17674	1.313662	0.00015
	Siman 2	0.068503	19.17674	1.313662	0.00015
	Sabzevar1	0.068503	19.17674	1.313662	0.00015
	Beihagh	0.068503	19.17674	1.313662	0.00015
	Sabzevar2	0.068503	19.17674	1.313662	0.000146
	Bashtin	0.066272	19.27995	1.277728	0.00015

The comparison of the proposed method with other methods presented in [2] and [15] are shown in Table VIII. [2] Investigates the reliability of a power substation with integrated smart monitoring devices. In order to calculate and compare the reliability of this substation with and without monitoring, a well-known model, which minimizes the load shedding while considering network constraints, is used. The EENS is calculated in Table VIII. Case study is the 400/63 kV substation with a breaker-and-a-half configuration.

TABLE VII
RELIABILITY INDICES AND COSTS FOR IMPERFECT MAINTENANCE MODELS

Terminal	Energy consumption (MWh/yr)	Without CM		With CM	
		EENS (MWh/yr)	Reliability Cost ($/yr)	EENS (MWh/yr)	Reliability Cost ($/yr)
Esfarayen	56227	1.698492	4246.23	0.793207	1983.018
Maiamey	2136889	64.55064	161376.6	30.14558	75363.95
Neyshabour	1855	0.057533	143.8326	0.027667	69.16652
Modarres	545650	16.89395	42234.87	8.108703	20271.76
Electeric	26257	26.82876	67071.9	3.936945	9842.364
Dasht Jov	3344	3.416817	8542.043	0.501396	1253.489
Siman1	57425	58.67546	146688.7	8.610241	21525.6
Siman2	26652	27.23236	68080.9	3.996171	9990.428
Sabzevar1	155861	159.255	3.98×10^5	23.36963	58424.06
Beihagh	166330	169.9519	424879.8	24.93934	62348.34
Sabzevar2	153719	157.0663	392665.8	23.04846	57621.14
Bashtin	209559	213.7761	534440.4	30.56169	76404.22
Total	3539768	899.4033	2248500	158.039	395100

In [3] the maintenance of overhead lines in a transmission system located in the southwest of China is used as an example. The system supplies a total load of 5473 MW and has 182 buses and 240 branches. Seven lines were identified as abnormal according to normalized condition indices, which were calculated from condition monitoring data in two cases 1&2, and thus were selected to be the candidates for maintenance. These lines are denoted by L1-L2 in the paper. The EENS is calculated in Table VIII.

TABLE VIII
COMPARISON OF THE PROPOSED METHOD WITH OTHER METHODS PRESENTED

Row	Reference		Indices	Without CM	With CM	Improvement (%)
1	[2]		EENS (%)	0.096	0.0444	53.75%
2	[15]	Case1	EENS(Mwh/yr)	24514.6	20751.8	15.34 %
		Case2	EENS(Mwh/yr)	21170.1	20282.1	4.19 %
3	Proposed model		EENS(Mwh/yr)	899.4033	158.039	82.43 %

D. Examination Proposed Markov models in KREC

In this section, the mean duration of inspections, minor maintenances, major maintenances and replacement in CBs 400KV are considered 2-hours, 2-day, 7-day and 0.2-year, respectively. The Costs of inspection, minor maintenance, major maintenance and replacement are U.S. $ 350, 1240, 6000, and 80000, respectively. In CBs 132KV, the mean duration of inspections, minor maintenances, major maintenances and replacement are considered 1-hours, 1-day, 3-day and 0.1-year, respectively. The Costs of inspection, minor maintenance, major maintenance and replacement are U.S. $ 250, 1000, 3500, and 40000, respectively. In addition, λ_1, λ_2 and λ_3 are 0.33, 0.29 and 0.5, respectively. Inspection rates γ_1, γ_2 and γ_3 in the PM and the proposed Markov models are periodic and equal to 1 (1/year).

The parameters of Markov model and costs of CBs 132KV and CBs 400KV by applying the PM model and the proposed Markov model have been calculated in Table IX in accordance with Equs. (20)-(27). It must be noted that the cost of CM devices is considered in the costs for the proposed Markov model. Using the proposed Markov model, we can calculate the effect of CM devices on the lifetime of the CBs. Table IX shows lifetime of the CBs 132KV and 400KV, which showed an increase of 12.1349 and 12.1350 years respectively. By examining costs, equipment replacement costs and maintenance costs in the Markov model are reduced compared to those for the PM model. The cost of CM devices on the CBs of substation is 10,000 ($/Device). The cost of CM devices in Table IX is divided into the useful life of the CBs.

TABLE IX
TIME BASED INDICES AND COSTS FOR PM AND PROPOSED MARKOV MODELS (132KV)

State	132 KV		400 KV	
	PM [7]	Proposed model	PM [7]	Proposed model
MTTR(years)	36.8732	49.0081	36.82516	48.2545
MTTF from S_1(years)	36.7662	48.9012	33.79417	45.22351
MTTF from S_2(years)	33.7356	45.8706	24.93231	32.03549
MTTF from S_3(years)	24.8857	32.5678	37.04806	48.4774
Inspection Cost ($/years/Device)	248.9216	252.2502	397.8615	211.9182
Minor Maintenance Cost ($/years/Device)	274.8156	242.8712	339.163	298.0111
Major Maintenance Cost ($/years/Device)	233.1865	122.6153	346.8454	350.73
Replace Cost ($/years/Device)	1084.799	816.1905	2159.357	1650.253
Maintenance Cost ($/years/Device)	1841.7227	1433.9272	3243.227	2510.912
Repair Cost ($/years/Device)	3.4260	0.3434	4.9374	1.5699
Sensor Cost ($/years/Device)	0	207.2346	0	207.2346

TABLE IX CONTINUED

E. A Cost-benefit analysis to CM devices on the CBs

EENS is obtained by multiplying the probability of loss each terminal and the output energy of each terminal in the year. The Value Of Lost Load (VOLL) is assumed 2500 ($/MWh), in KREC. A Cost-benefit analysis to CM devices on the CBs is done in Table X. Table X shows the EENS, reliability cost, maintenance costs, repair cost, cost of CM devices and the total cost of substation in two statuses; without CM and with CM. As illustrated in Table X, the EENS and reliability cost of substation which CBs to be equipped with CM devices have improved by 82.43% compared to that for conventional substation. The maintenance cost of the proposed model improves by 9.07 % compared to PM model. Finally, 80.67 % saving will be on the total annual cost due to CM on CBs.

TABLE X
A COST-BENEFIT ANALYSIS TO CM DEVICES ON THE CBS

Substation 400/132/20	without CM	with CM	Percent Prevent
EENS (MWh/yr)	899.4033	158.039	82.43 %
Reliability Cost ($/yr)	2248500	395100	82.43 %
Maintenance Cost ($/yr)	49447.9927	44962.2422	9.07 %
Repair Cost ($/yr)	82.1226	17.9065	78.20 %
Sensor Cost ($/yr)	0	4144.692	-
Total Cost ($/yr)	2298030.1153	444224.8407	80.67 %

VII. CONCLUSION

The CM devices are wildly used in power substations. The results of the analyses of the present study using this technology on the CBs of substations showed that the CM devices of CBs improve the reliability of substation while decreases reliability cost. The first innovation of the paper was providing a mathematical model to calculate various types of failure rates. Using that, the effect of CM devices on failure rates was modeled. The other novelty of the paper was to propose new integrated preventive and predictive maintenance Markov model for analyzing the effect of CM devices on the maintenance process. This paper shows that by CM, the number of failures that require major maintenance are detected early and corrected in scheduled outage or emergency outage. Using the Minimal Cut-Set method, the reliability index of EENS for each substation terminal is calculated. Finally, the failures of CB in KREC in Iran were studied. The results obtained show the outage probability of the terminals substation and the reliability cost of substation experienced improvement.

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