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Prioritization approach for circuit breakers to equip with condition monitoring devices

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Abstract: Circuit Breakers (CBs) play an important role in ensuring the safe operation of protection systems. Condition Monitoring (CM) devices are widely implemented to extend lifetime, and to improve the maintenance quality. The present paper proposes a cost-based prioritization approach for CBs in a network equipped with CM devices. To this end, a mathematical formulation is developed for the categorization and modeling of equipment failures based on their severity. This formulation quantifies the effect of the CM devices on the outage rate of the equipment. The reliability parameters of the substations 400/132/20 KV, including the failure rate, λ, average repair time, r, average outage time, U, substations, in two status of without CM and with CM of the CBs are calculated. These parameters are calculated implementing a minimal cut-set method. The outage rate of equipment with and without the CM devices is used to determine the effect of the CM devices on the reliability of the network. Finally, the prioritization of substations to install the CM devices on the CBs has been investigated in terms of the Expected Energy Not Supplied (EENS) and costs of CM. To verify the effectiveness and applicability of the method, the proposed approach is applied to the CBs in the power transmission network in the Khorasan Regional Electricity Company (KREC) in Iran.

Key words: circuit breakers, condition monitoring, outage rate, reliability, smart sensor

1. Introduction

1.1. Motivation

The Condition Monitoring (CM) systems are wildly used currently in power substations to monitor the health condition of a piece of equipment [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 the 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 considers 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 large-scale instances of the proposed maintenance-scheduling model. Extensive computational studies using real-world degradation data demonstrates the effectiveness of the new framework.

Substation equipment with CM has a direct impact on the reliability studies and the maintenance scheduling of the network. The failures of a CB, considered as one of the key elements of the substation, accounts for around 39% of the failures [6]. Therefore, the CM of CBs can improve the reliability of the substation, while decreasing the annual unreliability cost.

1.2. State of the art

The scheduled maintenance is commonly divided into Preventive Maintenance (PM), Condition-Based Maintenance (CBM) and Predictive Maintenance (PDM). In the PM, the inspections and maintenance process is performed periodically on the equipment. The PM activities are often modeled using a classical state diagram with a periodic inspection rate [7–9]. The maintenance activities are modified to increase the frequency of inspection based on knowledge of the level of equipment failure so that non-periodic inspection rates could be introduced to illustrate state diagrams in maintenance modeling [10–16]. The probabilistic Markov maintenance models are used to quantify the effect of various inspections and maintenance rates on the equipment lifetime and the associated costs [17–20]. Optimal inspection and maintenance rates reduce the costs associated with the equipment replacements while improving the equipment lifetime [17, 18]. The organization of the maintenance process of the system components based on the reliability of the system is known as Reliability-Centered Maintenance (RCM) which is discussed comprehensively in [11, 18]. Some studies reported in the literature [21] were aimed at determining the optimal maintenance strategy for an electric power supply as a realistic complex system with a given reliability constraint. In recent decades, there has been observed a rapid increase in the number of studies on CBM, partly due to the recent development of monitoring technologies. The proper design of the CBM can be effective in improving the reliability of equipment [22, 23]. Reference [23] presents a review of the CBM research studies. Reference [24] presents two main challenges in strategies for periodical maintenance. Firstly, many actual engineering systems have complex characteristics, so it is not a wise decision to follow fixed inspection strategies for every system. Secondly, a fixed interval inspection cannot be tailored in practice through increasing the operation time of equipment. Hence, a mixed time/condition-based probabilistic maintenance model is proposed in this reference. In [25], implementing different maintenance approaches on a mechanical component to compare their relative benefits, concluding that, in general, the advanced CBM and PDM policies are associated with a relatively better performance. However, the PM shows a more desirable performance in some situations. Reference [26] 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 PM activity. In [27], a maintenance strategy is proposed for the overhead lines based on condition monitoring and the reliability of the network. To this end, it quantifies the relationship between the CM data and the failure rate of overhead lines. Then an EENS index is calculated using the new failure rates of overhead lines. Reference [28] presents a new probabilistic aging failure model for CBs equipped with the CBM. It is numerically applied to two common types of CBs, that is, SF6 and minimum oil based on the field data to reveal effects of the real aging and dynamic behavior of CBs on cost/benefits of maintenance policies.

1.3. Gap in the research

In the literature, the failures of the equipment are not well categorized and formulated. In addition, failures leading to the outage are not well separated from other failures. The model calculation of the failure rate and repair time is implemented for only one type of substation scheme. As mentioned in the literature on CBM, the use of CM devices does not mean that the PM is not required. By the CM and early detection of minor failures, requirement based maintenance, which is referred to as PDM, can be added to the periodical maintenance schedule. In many literatures, the model calculation of the failure rate and repair time is implemented for a substation and network only and is not investigated. In the CM, the probability of the CM devices failure is not investigated. Moreover, more studies seem necessary for the prioritization of the substations to applying the CM devices based on the annual unreliability cost. This paper has tried to cover the deficiencies outlined in other researches.

1.4. Contribution

In this paper, a cost-based prioritization approach is proposed for a CB in a network equipped with CM devices. To this end, a mathematical-simulation procedure is extended in three steps in this paper, as shown in Fig. 1.

Step 1: The unique novel idea, the first step is to provide a mathematical formulation to categorize and model the failures of the equipment based on its severity. The CM employs information from multiple sensors. The failure probability of smart sensors has been taken into account. In fact, by the CM, some of the severity failures, named major failures, can be detected and corrected as minor failures. The proposed mathematical formulation quantifies the effect of the CM on the outage rate of the equipment. The outage rate is used in step 3 to study the reliability of the equipment in the presence of the CM devices in the network.

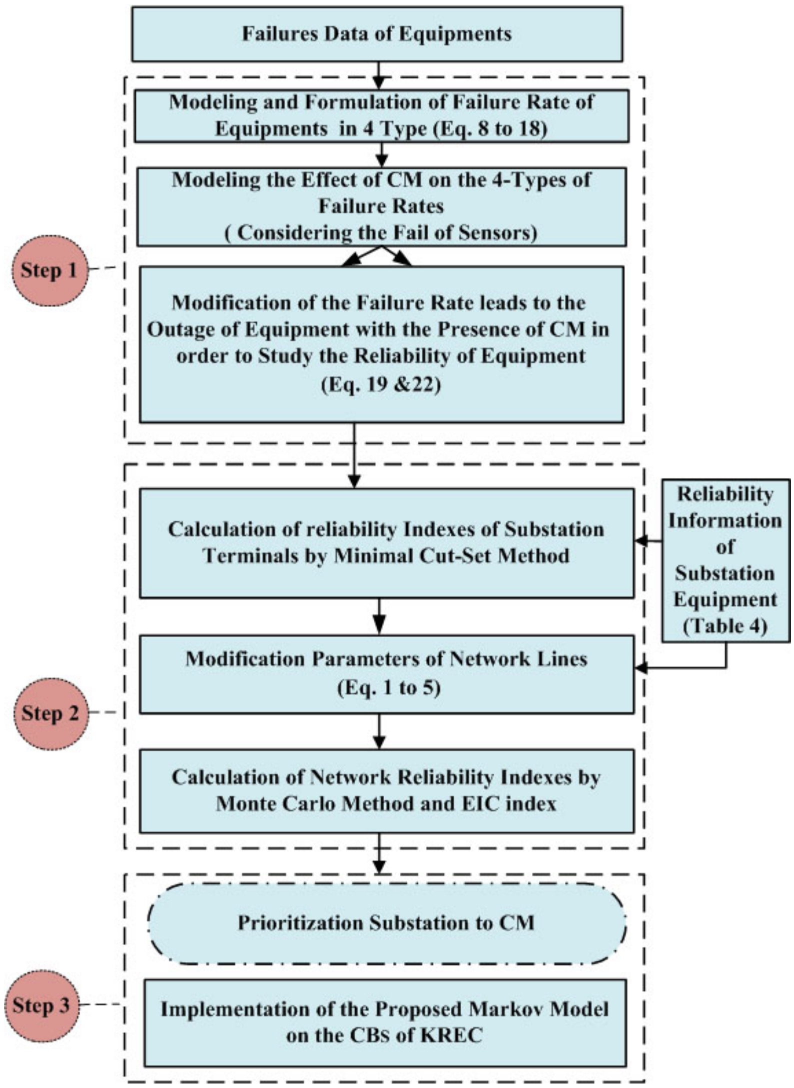

Fig. 1. Flowchart of substations' cost-based analysis for CM

Step 2: At this step, reliability methods used to calculate failures of the substation equipment [29]. By monitoring the status of the equipment, the failure rate of the substation equipment, including the CBs, will improve and the network reliability level will increase. In order to quantify this improvement first, a minimal cut set method is implemented to calculate the reliability indices of the substation in two different states (with and without CM). Then, the modified reliability parameters of transmission lines are obtained with regards to the reliability of the series elements. Finally, the Monte-Carlo simulation method is used to calculate the total EENS of the network and Expected Interruption Cost (EIC).

Step 3: In the third step, prioritization of the substations is performed to install the CM devices on the CBs considering the reliability. The prioritization of the substations is based on minimum EENS and C_{Total}. Finally, the proposed approach for verification of the method is applied to the CBs in the power transmission network in the Khorasan Regional Electricity Company (KREC) in Iran.

The novelties of the paper are as follows:

1. Presentation of the new mathematical model of equipment failures (Step 1):
   1.1. Proposing an innovative mathematical model to categorize the types of equipment failures and determine the failure rates.
   1.2. Development of the proposed mathematical model to calculate the effect of the CM devices on the failure rates of equipment.
   1.3. The failure probabilities of sensors are also modeled.
2. A cost-based prioritization approach is proposed to the CM on the CB of the network (Step 2):
   2.1. Using a minimal cut set method, the reliability indices of the terminals of each substation consist of the failure rate and repair time, are calculated in two states of with and without the CM.
   2.2. The modified reliability indices of transmission lines are obtained considering the reliability of the series elements. Using the Monte-Carlo simulation method, the total EENS of the power transmission network and EIC are calculated.
   2.3. Prioritization of substations is based on improving the EENS and cost of the CM devices calculated.
3. Apply the proposed method on 400KV CBs of the KREC with a Comprehensive statistical study (Step 3).

1.5. Article structure

In the next section, the reliability evaluation of a substation and network are investigated. In the third section, the failure rates of equipment with and without CM devices are dealt with. In Section 4, the objective function is introduced. The five-section deals with case studies. Finally, some conclusions are drawn from the obtained results in the sixth section.

2. Reliability evaluation of substation and network

A minimal cut-set method is the conventional method for evaluating substation reliability. A cut-set is a set of system elements whose failures cause a system failure. A cut-set is said to be minimal if, when any of its elements has remained, the system remains proper. 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 a minimal cut-set are parallel to each other in terms of a 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 power supply. Therefore, the reliability of each cut-set depends on the reliability of the parallel equipment. Equation (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 [30].

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

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

$$\lambda_s = \sum_i \lambda_i, \qquad U_s = \sum_i \lambda_i r_i, \qquad r_s = \frac{U_s}{\lambda_s}, \tag{2}$$

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 average outage time [30].

In this paper the 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 substation. The RCOPS program examines the reliability of substations with the help of the minimal cut-set. Fig. 2 shows the flowchart of a sub-program of the RCOPS that calculates the reliability of the substation.

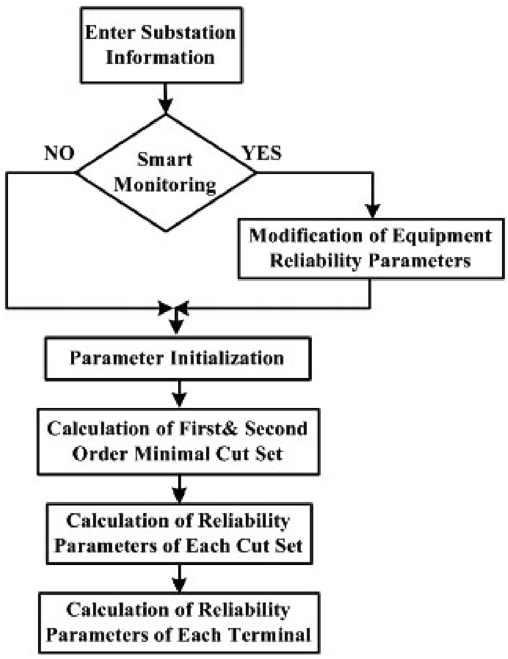

Fig. 2. The process of calculating the reliability of each substation in RCOPS

To evaluate the reliability of the substation with the help of the minimal cut-set, the substation schema and reliability parameters of the substation (CB number, λ, and r) are considered as input. In the third section, the calculation of the failure rate, λ, will be explained. The repair time depends on the amount of equipment damage. The failure rate and repair time of each terminal of the substation is calculated as the RCOPS output. To evaluate the reliability of the network with the help of the Monte-Carlo simulation method, the reliability parameters of the transmission lines are modified as shown in Fig. 3. The modified failure rate and repair time of the transmission line in Equations (3)–(5) are calculated [29].

$$\lambda_{\text{new}} = \lambda_{\text{old}} + \lambda_{\text{set}_1} + \lambda_{\text{set}_2}, \tag{3}$$

$$U_{\text{new}} = U_{\text{old}} + U_{\text{set}_1} + U_{\text{set}_2}, \tag{4}$$

$$r_{\text{new}} = \frac{U_{\text{new}}}{\lambda_{\text{new}}}. \tag{5}$$

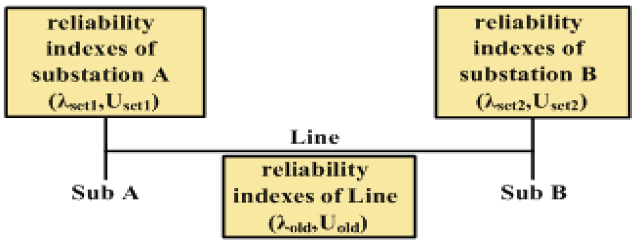

Fig. 3. The modified failure rate and repair time of the transmission line

By using the modified reliability parameters of the network, the Expected Energy Not Supplied (EENS) index is calculated based on the Monte-Carlo simulation method, using DIgSILENT Power Factory software. The total EENS of the system is obtained from the summation of the EENS of all buses in Equation (6), [31].

$$\text{EENS} = \sum_{n} \text{EENS}_n . \tag{6}$$

The Expected Interruption Cost (EIC) is calculated by multiplying the EENS with the Value of Lost of Load (VOLL) in Equation (7).

$$\text{EIC}\ (\$/\text{yr}) = \text{EENS}\ (\text{Mwh/yr}) \times \text{VOLL}\ (\$/\text{Mwh}). \tag{7}$$

Certainly, as the failure rates of CBs improve using CM, the EENS and EIC show a decrease.

3. Analytical modeling of equipment failures

3.1. The effect of equipment failure on reliability without CM

For the analytical modeling of the effect of equipment on reliability, it is necessary to model the failure factors along with their failure frequency in the equipment. Equation (8), shows the set of failures of equipment A, which includes the X type of failure:

$$A = \{A_x\}, \qquad x = 1, \ldots, X, \tag{8}$$

where A_x is the failure type x of equipment A. The total number of failures for the N equipment of type A, in the study period of T, is calculated with Equation (9).

$$n_A = \{n_x\}, \qquad x = 1, \ldots, X. \tag{9}$$

In Equation (10), the general relation of the failure rate of equipment A is expressed based on the failure type x:

$$\lambda_x = \frac{n_x}{N.T}\,. \tag{10}$$

In this paper, failures are divided into four categories, based on their severity.

1. The failure x does not create a problem for the system; in fact, there is a minor failure. Therefore, it can be waited for its maintenance, and will be corrected in the scheduled outage. In this case, the failure rate of equipment A, which can be corrected in the scheduled outage, is defined by Equation (11).

$$\lambda_M = \sum_{x=1}^{k} \lambda_x M_x\,, \tag{11}$$

which:

$$M_x = \begin{cases} 1 & \text{Failure } x \text{ will be corrected in scheduled outage} \\ 0 & \text{Other} \end{cases}. \tag{12}$$

2. The failure x is corrected in on-loaded repair while there is 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 by Equation (13).

$$\lambda_p = \sum_{x=1}^{k} \lambda_x P_x\,, \tag{13}$$

which:

$$P_x = \begin{cases} 1 & \text{Failure } x \text{ can be corrected in on-loaded repair} \\ 0 & \text{Other} \end{cases}. \tag{14}$$

3. The failure x is important and requires immediate action of 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 the emergency outage of repair team is:

$$\lambda_E = \sum_{x=1}^{k} \lambda_x E_x\,, \tag{15}$$

which:

$$E_x = \begin{cases} 1 & \text{Failure } x \text{ requires an emergency outage} \\ 0 & \text{Other} \end{cases}. \tag{16}$$

4. The failure x causes trip of equipment A. In fact, there is a major failure; these types of failures construct the outage rate of the equipment in Equation (17).

$$\lambda_T = \sum_{x=1}^{k} \lambda_x T_x \,, \tag{17}$$

which:

$$T_x = \begin{cases} 1 & \text{Failure } x \text{ causes equipment outage} \\ 0 & \text{Other} \end{cases} . \tag{18}$$

It must be noted that many of minor failures are corrected before they become major failures in PM. The maintenance team in PM and the emergency outage of the equipment (and not the trip of the equipment) correct the failures of type 1, 2, and 3. These kinds of failures will not result in unwanted loss of load. However, the failures of the fourth type, which the authors of the paper are attempting to reduce by installing CM devices, are the trip failures and may cause the loss of load. Regional power companies are looking for reducing this type of outage.

3.2. The effect of equipment failure on reliability with CM

The CM allows operators to observe failures more easily and quickly. Such actions significantly reduce the failure rate and repair time. If the failure of x is of the fourth type ($T_x = 1$), which can be 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, Equation (19) defines the outage rate of equipment A when the CM devices detect the failures.

$$\lambda_{T\text{new}} = \sum_{x=1}^{k} \lambda_x (T_x - S_x T_x), \tag{19}$$

where:

$$S_x = \begin{cases} 1 & \text{Failure } x \text{ is detected by CM devices} \\ 0 & \text{Other} \end{cases} . \tag{20}$$

According to Equation (19), when all sensors are healthy and detect failures, decreases of the number of failures detected from the failure list lead to output equipment. As a result, the failure rate is reduced according to Equation (19). Now suppose one or two sensors are defective, (failures are not detected), of course, the failure rate, in this case, will increase compared to the failure detection by the sensors, where we always have:

$$E_x + P_x + M_x + T_x = 1. \tag{21}$$

Equation (21) guarantees each type of failure only belongs to one of the failure categories. By using the conditional probability method, the outage rate of equipment A in Equation (19) can be modified in Equation (22), considering the probability of failure of the CM devices:

$$\begin{aligned}\lambda_{T\text{new}\bullet} = \lambda_{T\text{new}\bullet}\left(\prod_{s=1}^{S} P_s\right) + \sum_{m=1}^{S}\left(\lambda_m\left(\prod_{s\neq m} P_s\right)Q_m\right) + \\ + \sum_{n}\sum_{m}\left(\lambda_{n,m}\left(\prod_{s\neq n,m} P_s\right)Q_nQ_m\right) + \ldots,\end{aligned} \tag{22}$$

where λ_m is the outage rate A, assuming the proper function of all the CM devices except the CM device m. $\lambda_{n,m}$ is also the equipment outage rate, assuming the proper function of the CM devices except for the CM devices n and m. In this study, it is assumed that the probability of simultaneous failure of two CM devices and more is equal to zero.

The new failure rate applied to the RCOPS program is used to calculate the failure rate and repair time with the CM. The first term on the right side of the parity of Equation (22) relates to a state in which all sensors are healthy. Therefore, concerning the independence of the failure of the sensors from each other, the probability of occurrence of this state is equal to the product of multiplying the probability that each of them is healthy $\left(\prod_{s=1}^{s} P_s\right)$. Of course, in this case, the failure rate of the equipment is the same failure rate with the presence of all sensors that are named $\lambda_{T\text{new}}$ in this paper. The second term on the right side of the parity of Equation (22) relates to all the states in which a sensor may be failed. The probability of all the sensors being healthy except the m sensor is. $\left(\prod_{s\neq m} P_s\right) Q_m$. In this case, the study of equipment failures is the same as before but without regard to the m sensor. Similarly, the third term on the right of Equation (20) expresses all the states of the simultaneous failure of the two sensors m and n, which occurs with probability $\left(\prod_{s\neq n,m} P_s\right) Q_nQ_m$.

The cost of installing smart sensors on the power transmission network CBs is defined by C_{CM} which is (\$/device).

4. The objective function of prioritization of substations for CM devices

The purpose of this paper is to prioritize substations of the network to CM on a CB, based on the cost function proposed in Equation (23).

$$C_{\text{Total}}^{\$/\text{yr}} = \sum_{i=1}^{k} \text{EIC}_i(\$/\text{yr}) + C_{\text{CM}}(\$/\text{yr}), \tag{23}$$

where k is the number of substations of the network and the C_{CM} is the cost of installing smart sensors. The effects of the CB failure on the EENS and the EIC depend on the substation location in the network and the substation scheme. The proper prioritization of the substations to equip CBs to the CM devices will effectively reduce the EENS and EIC. Therefore, appropriate prioritization is likely to decrease the annual cost and outages, while improving network reliability.

5. Case study

In this section, the proposed approach is applied to the CBs of the power transmission network in Iran so that the effectiveness and applicability of the method can be demonstrated.

5.1. The statistical study of CB failures in the KREC

In this section, the failures of 400-KV SF6-CBs during 4 years, from 2014 to 2017, and the effect associated with the application of CM on CBs have been studied. The network contains 17 substations, 26 transmission lines, and 99 CBs. In Table 1, the values of M_x, P_x, E_x, T_x, and S_x of the CBs are determined in accordance with Equations (12), (14), (16), (18) and (20), respectively. Also, based on Equations (10), (11), (13), (15) and (17), the rates of the four failure types of CBs are calculated. We classify the failures in two steps:

In the first step, failures are classified according to their types. For instance, "low pressure of SF6 gas" is one of the conventional failures of CBs. The failure rate of this type of failure (λ_x) is calculating using Equation (10). In this equation n_x is the number of occurred failures. The "low pressure of SF6 gas" failure 4 times happened in the 4 years study among 99 CBs. So, in Table 1, λ_1 is 4/(4*99) which is equal to 0.0101 (f/yr). This classification helps the author to determine the failures which can be identified by sensors (CM). S_x in Equation (20) indicates this identification. For example, the "low pressure of SF6 gas" failure can be identified by pressure sensor.

In the second step, failures are classified according to their severities. The high severity failures cause the tripe of a CB. According to Equation (19), if there is a sensor to identify the failure type x ($S_x = 1$) and this failure trips the CB ($T_x = 1$), so by using the CM this type of

Table 1. The set of failures occurred in CBs of power transmission network 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 the 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

failure is removed from high severity failures. So, by using the CM some of the high severity failures can be early identified to prevent the tripe of the CB. The proposed model quantifies this improvement. A_x in Equation (8) is the failure type x of equipment A and occurs with the failure rate λ_x(f/yr). This type of failure belongs to the one category of failures based on its severity and is indicated by the values M_x, P_x, E_x, and T_x. It must be noted that Equation (21) guarantees each type of failure belongs to one of the failure categories only. For example, the failure type A_1 in Table 1 with the failure rate $\lambda_1 = 0.0101$ has values of $M_1 = 0$, $P_1 = 0$, $E_1 = 0$ and $T_1 = 1$. Therefore, according to Equations (11), (13), (15) and (17), the values of λ_1 only appears in λ_T. However, the failure type A_2 with the failure rate $\lambda_2 = 0.0025$ has the values of $M_1 = 0$, $P_1 = 0$, $E_1 = 1$ and $T_1 = 0$. Therefore the values of λ_2 only appear in λ_E in Equation (15).

5.2. Analysis of the effect of CM on the CBs of the KREC

In this paper, it is assumed that two sensors S_1, an acoustic emission sensor, and S_2, a pressure sensor, are installed for CM of a CB. The set of failures that are detected by S_1 is A_{11} and S_2 is A_1, A_{12}, and A_{13}. In Table 2, Equations (17) and (19) are used to determine outage rates of CBs before and after the CM as 0.030303 (f/yr) and 0.012626 (f/yr), respectively. If the failure probability of the sensor is considered as 0.001, the outage rate of CBs increases to 0.012661, which is calculated by Equation (22). Therefore, by the CM, the outage rate of the CBs improves by 58.22%. The cost of installing smart sensors S_1 and S_2 on the power transmission network CBs is 250 ($/yr/device).

Table 2. Failure rates of 400 kV CBs in different states

CB	λ_T	$\lambda_{T\,\text{new}}$	$\lambda_{T\,\text{new}}$
400 KV	0.030303	0.012626	0.012661

5.3. Calculation of the reliability indices of the KREC

Three samples of a 400 KV substation of the KREC are shown in Figs. 4–6. Substation 1 in Fig. 4 has a one-and-a-half breaker scheme with nine CBs, four output terminals and two 400 kV bus bars. Substation 2 in Fig. 5 has a double bus bar scheme with 18 CBs, six output terminals and two 400 kV bus bars. Substation 3 in Fig. 6 has a ring scheme with four CBs, four output terminals and two 400 kV bus bars.

A minimal cut-set method is implemented to evaluate the reliability of each substation. Table 3 summarized the results related to the failure rate, repair time and the loss of terminals of sample substations with and without CM devices when a minimal cut-set method is used. Due to the symmetry in the substation 1 scheme, the reliability indices of all terminals are similar. According to Equation (19), when all sensors (S_1 and S_2) are healthy and detect failures, some of the failures detected from the failure list lead to output equipment and this way decreases. Now, suppose one or two sensors are defective, (failures are not detected), of course, the failure rate, in this case, will increase compared to the failure detection by the sensors. The new failure rate according to Equation (22), which applies to the RCOPS program, is used to calculate the failure rate and repair time with the CM.

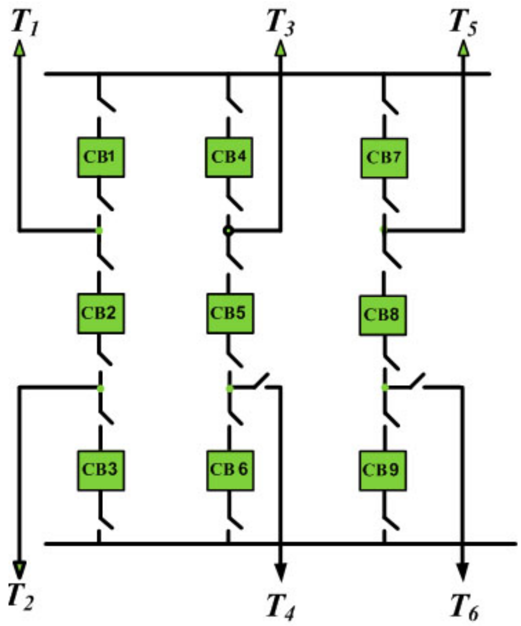

Fig. 4. Substation 1 of the KREC

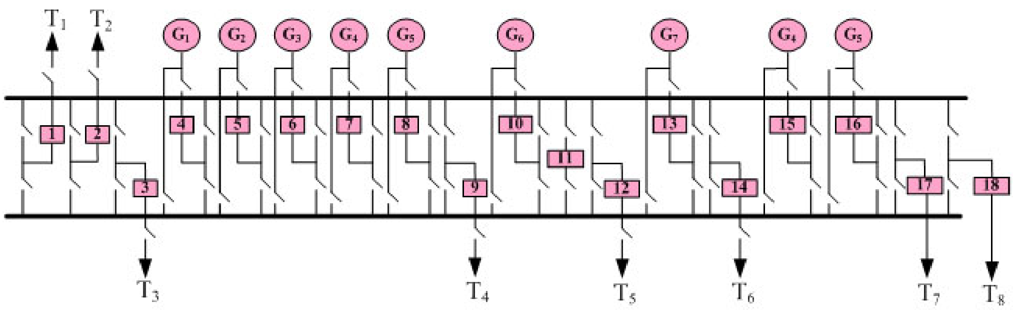

Fig. 5. Substation 2 of the KREC

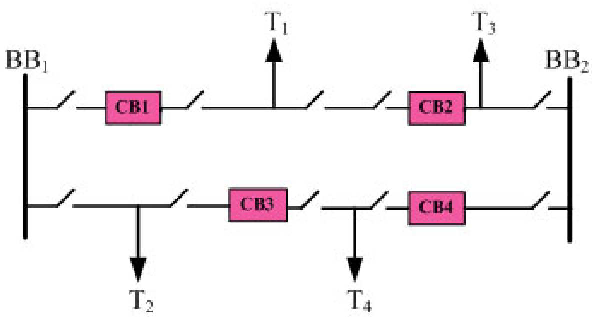

Fig. 6. Substation 3 of the KREC

The power transmission network of the KREC is shown in Fig. 7. The network is made up of 17 substations with a perfect one-and-a-half CB scheme, and an incomplete one-and-a-half CB scheme, a double bus-bar, and a ring are all connected to 26 transmission lines.

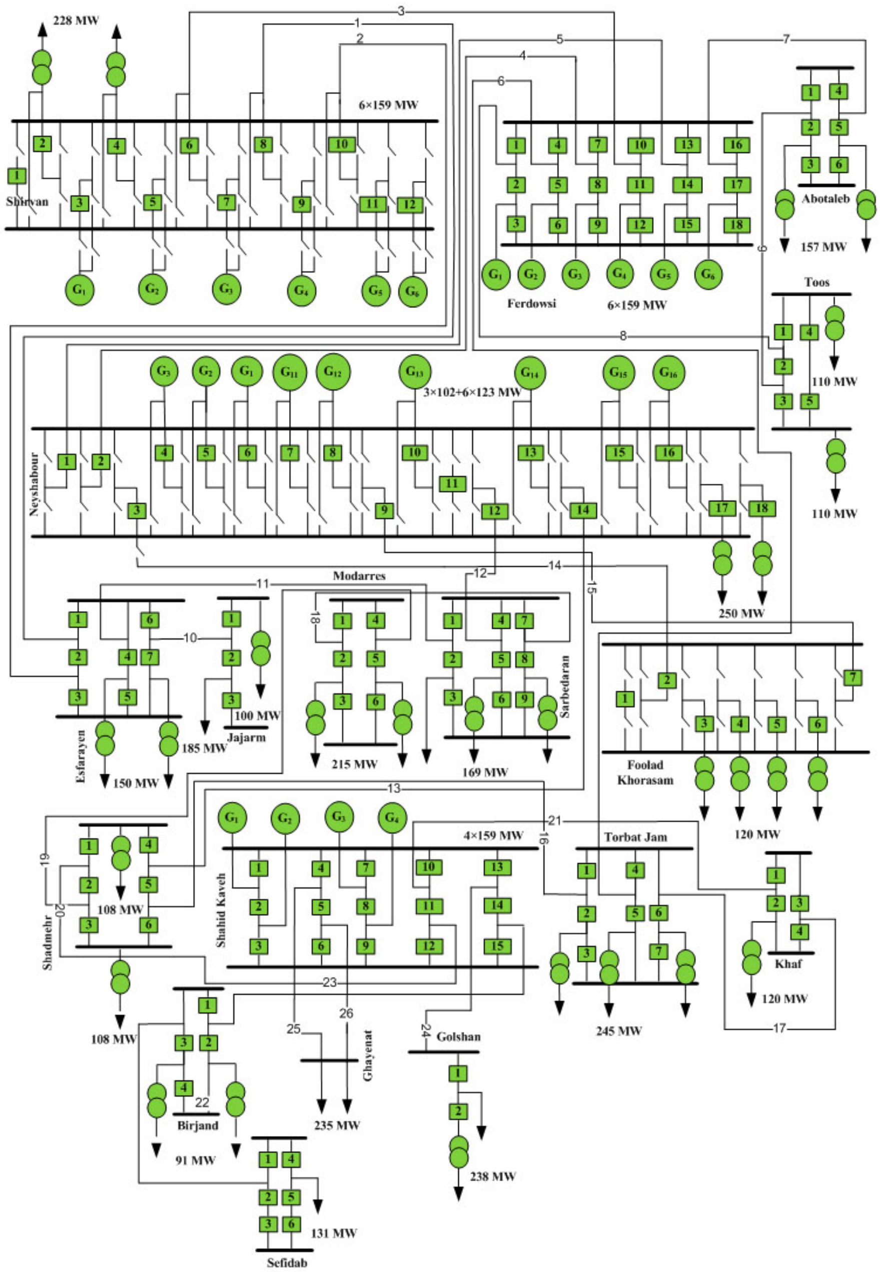

Fig. 7. Power transmission network of the KREC

Table 3. Reliability indices of three samples of a 400 kV substation of the KREC

Substation	Terminal	Without CM			With CM		
		λ	R	U	λ	R	U
1	T_1–T_6	0.037828	6.994939	0.264602	0.02236	5.508042	0.123161
2	T_1–T_7	0.0754	6.8516	0.5168	0.0385	6.5684	0.2528
	T_8	0.0723	0.0723	0.4843	0.0338	6.2536	0.2115
3	T_1 and T_3	0.0039	5.4510	0.0211	0.0023	5.2776	0.0123
	T_2	0.0328	8.3271	0.2734	0.0159	7.7849	0.1236
	T_4	0.0296	8.6167	0.2547	0.0141	8.0397	0.1136

This network contains four power plant substations. The total capacity of power plants is 3299 MW, with the total network load being 3251.5 MW. The reliability information of the transmission network and substation equipment is presented in Table 4. Considering the failures of the substations, the reliability parameters of the transmission lines are corrected using Equations (3)–(5) so that the reliability of the network can be determined. The failure rate and the repair time of the modified transmission lines have been calculated with and without the CM devices. Finally, an EENS index is calculated implementing the Monte-Carlo simulation method, using DIgSILENT Power Factory software.

Table 4. Reliability information of the KREC equipment

Equipment	(f/yr)	(f/yr)	(f/yr)	(Hr)
	Active failure rate	Passive failure rate	Total failure rate	Repair time
Circuit breaker	0.0066	0.0303	0.0369	20
Bus bar	–	–	0.0064	8
Lines	–	–	8.0548E–05 (f/Yr/Km)	129.0384615

5.4. Prioritization of substations of KREC for CM devices

By applying the modified failure rates and the repair times of transmission lines, EENS is calculated at network using DIgSILENT Power Factory software. According to Equation (7), EIC is obtained. The Value Of Lost Load (VOLL) is assumed in 2500 ($/MWh) in the KREC. Table 5 shows the EENS index, EIC, C_{CM} and C_{Total} of the CM in the KREC. In each row of Table 5, it is assumed that only the CBs related to the substation are equipped with the CM devices and the other substations operate conventionally. The first row is the basic study without the CM devices. According to the second column in Table 5, best improvement in the EENS is related to the CM devices on the CBs of the Shahid–Kaveh substation with the 105 (MWh/yr) reductions in the EENS. In addition, the EENS index of the substations that are equipped with the CM devices and the other substations operating conventionally is shown in Fig. 8.

Table 5. Reliability information of the KREC equipment

Row	**Substation/smart**	$\sum$ EENS$^{(\text{Mwh/yr})}$	$\sum$ EIC$^{(\$/\text{yr})}$	$C_{\text{CM}}^{(\$/\text{yr})}$	$C_{\text{Total}}^{(\$/\text{yr})}$
0	No CM	2656.061	6640153	0	6640153
1	Shahid Kaveh	2550.893	6377233	3750	6380983
2	Neyshabour	2590.054	6475135	4500	6479635
3	Shirvan	2598.545	6496363	3000	6499363
4	Esfarayen	2604.437	6511093	1750	6512843
5	Birjand	2614.829	6537073	1000	6538073
6	Toos	2625.031	6562578	1250	6563828
7	Shadmeher	2625.454	6563635	1500	6565135
8	Modarres	2625.736	6564340	1500	6565840
9	Sarbedaran	2632.224	6580560	2250	6582810
10	Torbat Jom	2633.070	6582675	1750	6584425
11	Aboutaleb	2633.917	6584793	1500	6586293
12	Foolad Khorasan	2635.973	6589933	1750	6591683
13	Sefidabe	2637.580	6593950	1500	6595450
14	Kkaf	2639.065	6597663	1000	6598663
15	Jajarm	2640.254	6600635	750	6601385
16	Ferdowsi	2650.868	6627170	4500	6631670
17	Golshan	2653.966	6634915	500	6635415

By the use of the CM devices in substations, the highest decrease in the EIC of the KREC is related to the Shahid–Kaveh substation with 262920 ($/yr) reduction. In Table 5, the cost of the CM, C_{CM} ($/yr), is calculated by multiplying C_{CM} ($/yr/device) with the number of the CBs of each substation. Due to the number of CBs in each substation, the substation with many numbers of the CBs has the highest cost of the CM. Neyshabour and Ferdowsi substations with 18 CBs have the highest cost of the CM. The Golshan substation with two CBs has the lowest cost of the CM. The annual total cost includes the sum cost of the EIC and cost of the CM. the highest decrease in C_{Total} of the KREC is related to the Shahid–Kaveh substation with 6380983 ($/yr) reduction. Also, the C_{Total} index of the substations that are equipped with the CM devices and the other substations operating conventionally is shown in Fig. 9.

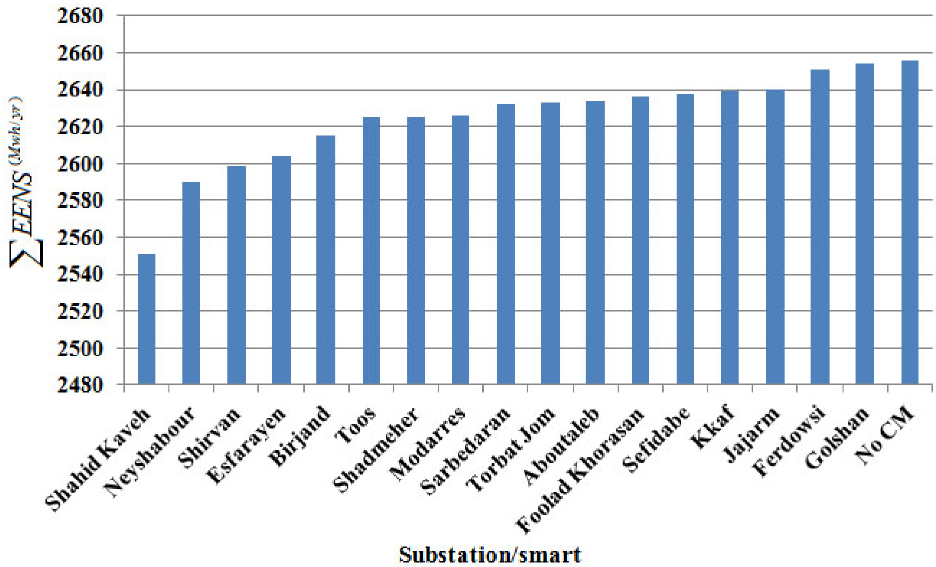

Fig. 8. EENS index of substations is equipped with CM devices and without it

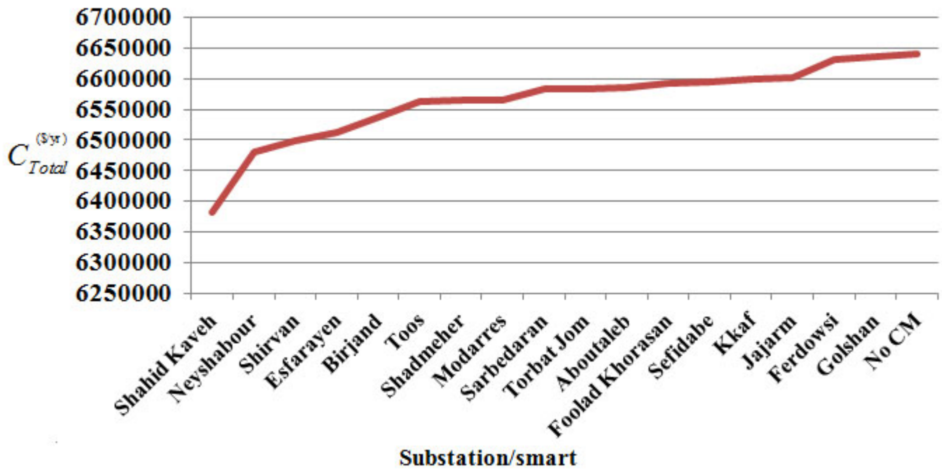

Fig. 9. C_{Total} index of substations is equipped with CM devices and without it

6. Conclusion

In the present study, CM devices, which are wildly used in power substations, were implemented on the CBs of substations to improve the reliability of the substation, and to reduce Expected Interruption Cost. The present study is novel and unique in two ways. Firstly, in the present study, a mathematical model is introduced to calculate various types of failure rates.

In this way, the effect of the CM devices on failure rates was modeled. Secondly, a cost-based prioritization approach for CBs in a network equipped with the CM devices is proposed. The following conclusions can be drawn from the simulation results.

– With the installation of two sensors, S_1, an acoustic emission sensor, and S_2, a pressure sensor, for CM of a CB, the outage rates of CBs before and after the CM as 0.030303 (f/yr) and 0.012626 (f/yr), respectively, are determined.
– With the failure probability of the sensor as 0.001, the outage rate of the CBs increases to 0.012661 and by the use of the CM the outage rate of the CBs improves by 58.22%.
– By using a minimal cut set method, the reliability indices of the terminals of each substation consist of the failure rate as well as repair time and are calculated in two states of with and without CM. Best improvement in EENS is related to the CM devices on the CBs of the Shahid–Kaveh substation with the 105 (MWh/yr) reductions in EENS. Thanks to the CM devices in the substations, the highest decrease in the EIC of the KREC is related to the Shahid–Kaveh substation with 262920 ($/yr) reduction.
– Prioritization of the substations is based on improving EENS and the calculated cost of the CM devices. Neyshabour and Ferdowsi substations with 18 CBs have the highest cost of the CM. The Golshan substation with two CBs has the lowest cost of the CM. The annual total cost includes the sum cost of the EIC and cost of the CM. The highest decrease in C_{Total} of the KREC is related to the Shahid–Kaveh substation with 6380983 ($/yr) reduction.

Along with the benefits of the CM of the substations' CBs, there are disadvantages and limitations that are:

– High installation cost of the CM devices used in the substation.
– Cost of the maintenance team to monitor the correct operation of the CM devices in the substation.
– Most sensors, such as pressure and acoustic sensors, operate at high frequencies (1 MHz), which causes resonance in them, therefore, the resonance frequency is a determining factor for the use of these sensors.
– The sensors must be perfectly designed to withstand dust and moisture and be resistant to high temperature environments.

Although this study tried to deal with aspects of CBM, there are still some shortages, which could be considered as future research works. For instance, some station oriented reliability evaluation techniques can be implemented resulting in the effect of the failure of equipment of scheduled maintenance. Prioritizing substations to install the CM devices on the CBs considering the annual total cost maintenance can be implemented.

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