Reactive energy compensator effect on the reliability of a complex electrical system using Bayesian networks

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Highlights

- A Bayesian approach for the electrical system reliability assessment is proposed.

- An industrial application was carried out on a real case of a complex electrical system.

- The role of STATCOM in electrical System reliability assessment has been shown.

Abstract

The static synchronous compensator is presented in order to improve an electrical network system performance. The present work aims to develop a Bayesian methodology for assessing the time-variant reliability of a complex electrical system taking into account reactive energy compensator (STATCOM). However, the complex aspect is not only related to the complexity of electrical system components architecture, nevertheless is allied to electrical network and STATCOM interactions. The Bayesian network is used for coping with this complexity constraint. The reliability-based assessment of reactive energy compensator effect is applied to a real case of a complex electrical system. The proposed Bayesian methodology application reveals that the STATCOM has a significant influence on electrical system reliability and the developed model can provide valuable information for decision makers to improve the system reliability performance.

Keywords

STATCOM, reliability, Complex Electrical System, reactive energy, Bayesian network.

1. Introduction

Modern society is increasingly dependent on electricity with a high reliability and required power supply [13]. Most industrial infrastructures require electricity for their operations and management. Electrical systems are, therefore, particularly critical. However, the operation of these systems may be subject to many risks, such as extreme weather conditions, natural risks, aging components, human error, animals and so on. Dysfunctions in electrical systems can cause severe and widespread socioeconomic damage [35], such the power outage affecting 2.5 million customers during the 1994 Northridge earthquake that hit Los Angeles. Moreover, the North American electricity outage in 2003 affected approximately 50 million customers. The industrial electrical network architecture is more complex depending on three main elements: voltage level, power required and supply security necessity. The purpose of electrical networks is to transmit energy from sources to consumption centers in an alternating current form interpreted by apparent power (S), which has two components: active power (P) and reactive power (Q) [50]. In fact, the voltage difference between the two ends of a line is linked to the reactive power transit consumed by the load. Harmonic pollution and reactive power loss are the two main problems of power quality (PQ) [26] and can introduce voltage distur-

bances, such as voltage dips, cause serious failures in electrical equipment and reduce electrical system reliability and efficiency [47].

The use of a static compensator (STATCOM) is an important solution to reactive power issues. STATCOM is a flexible alternative current transmission systems (FACTS) device based on power electronics [41, 49]. The above-cited device contains a voltage source converter that converts a direct voltage at its input terminals in a set of three-phase alternating voltages at a fundamental frequency with controllable amplitudes and phase angles [34]. As a matter of fact, the STATCOM voltage is injected in phase with the line busbar voltage V; in this case, there is no active energy exchange with the network, only reactive power is injected (or absorbed) by STATCOM [2, 3]. The electrical network consists of subsystems in a complex combination of series-parallel components as well as the STATCOM installation in the electrical system, implying a complicated system configuration and operation when the electrical network-STATCOM is not structured in series or in parallel.

In the general framework, high-reliability systems play definitive roles in industry. Furthermore, the industrial world is continuously evolving, which requires the development of new techniques that guarantee high reliability. Electrical systems have become increasingly complex and bulky; therefore, developing new methods to assess

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reliability and analyze systems behavior is a fairly important requirement for adapting to the industrial world's evolution [11]. Despite this, many methods have been developed, such as the fault tree [29], the reliability block diagram, the reliability graph and the Markov chain for evaluating reliability [19, 36, 46]. Besides, reliability analysis methods have been proposed in several studies by Monte Carlo sequential [45]. The simulation technique was desired to improve the reliability assessment of complex distribution systems; this analysis was implemented in practical tests [7]. Billinton et al. [6] illustrated a practical technique for evaluating the reliability of a complex radial electrical distribution system. The reliability of low-voltage distribution networks has been assessed by Guanglin et al. [17]. A detailed examination of reliability evaluations has been reported in [20, 31, 39, 51], and the study requires the modulation of large and complex systems in situations such as fault diagnosis and reliability assessments. The authors of the paper [30] presented a tool commonly used in the probabilistic reasoning of uncertainty in industrial processes. The work reported in [14] illustrated an approach based on Bayesian networks called the directed acyclic graph (DAG) and developed on Bayes' theorem and mathematical relationships. Obviously, the Bayesian method is one of the most appropriate methods to use in this context [1, 33]. According to Kelly and Smith [24], the Bayesian approach allows information and data to be combined for reliability assessments and fault probability estimations [21, 27]. A reliability evaluation can be obtained by converting traditional reliability models into the Bayesian network model. Moreover, system reliability can be obtained using occurrence probability techniques [30]. The BN approach is based on the Bayes theorem. Although this method seems somewhat similar to decision diagrams since it is a DAG that can be used to analyze the reliability of interdependent networks, the decision diagrams method is based on Shannon's decomposition [28]. The advantages of each of these methods are widely discussed [24, 38, 44, 48]. The efficiency of the BN method is characterized by its ability to accurately represent the modeling of time-dependent reliability as well as the treatment of uncertain and missing data [24]. Additional relevant information on the Bayesian approach may be found in Refs. [4, 22], where the BN models are more commonly used in probabilistic risk assessments (PRAs) and dependability analyses [24, 48].

The fact that electrical system reliability using STATCOM for energy compensation has not been studied in the existing literature, the present work's contribution is a developed model that can be applied in practical applications of electrical networks by taking into account the STATCOM effect and the given analysis regarding the real electrical system environment. The complex aspect is not only related to the complexity of the architecture of electrical system components but also extends to understanding the link and interaction between the electrical network and STATCOM. The remainder of the paper is organized as follows. First, the complex electrical system in the Algerian Company of Steel Industry is described. Then, a procedure for system reliability modeling supported by Bayesian networks is presented. Finally, the developed model is applied to the complex electrical system with and without STATCOM consideration, and the obtained results are analyzed and discussed.

2. System description

The system scheme where the study is conducted consists of several workshop units; the cold rolling mill (CRM) consumes much of the electricity. Energy production and distribution in the CRM are ensured by a highly complex electrical system that has specific operating characteristics, presenting a large difference compared to other industries and warranting many system functions such as (1) electrical supply of three tandem cages and skim pass inside ventilation, (2) overhead crane supply and (3) lighting and CRM control held at skim pass. The previous characteristics and coordination between the system components seem necessary to ensure a permanently reliable electrical system. The reliability analysis consequently aims at achieving a high-level of
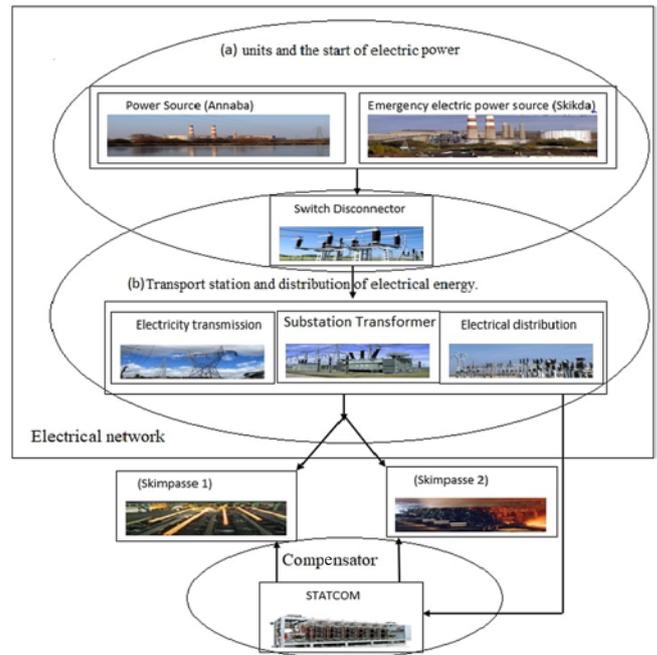

Fig. 1. Electrical system block diagrams

system functionality (production, transport and distribution). Different existing system functions generate a real complex scheme divided into several subsystems with well-defined components.

2.1. Electrical system configuration

The studied system is shown in Fig. 1 and provides electrical energy with more acceptable reliability. The electrical system is divided into two subsystems: STATCOM and the energy ensuring system. The latter is divided into two subsystems: (a) the unit's subsystem and (b) the electric power start. The step-down transport station and electrical energy distribution comprise the second subsystem.

The CRM is a massive unit that consumes a great amount of reactive energy, inducing many problems such as energy rate increases and higher costs, energy shutdowns in all substations and damage to devices and installation equipment. As a solution, the scheme requires a reactive energy compensator to avoid these issues and optimize its internal networks. The proposed device, called STATCOM, is a voltage source converter (VSC) connected in shunt via automatic switching devices like gate turn-offs (GTO) used for reactive power control [2]. The STATCOM, placed in the middle of Fig. 1, aims to control the voltage and improve the power quality [3, 40, 42]. As a complex system, a Bayesian network is introduced in this work in order to improve the reliability analysis of the presented system.

3. Procedure for modeling system reliability by Bayesian Networks

3.1. Bayesian networks

Bayesian networks (BNs) have been used in recent decades in the reliability and risk analysis of complex systems, Weber et al. [48] present a detailed review and introduce BNs' basis by explaining their importance in modeling complex systems. The BN is a DAG in which the nodes represent the system variables and the arcs represent the dependencies or direct causal relationships among these nodes. The variables may be discrete or continuous, and the arc is a set of directed links (arrows) that connect pairs of nodes. If there is an arrow from node X to node Y, then X is said to be a parent of Y, and each node Xi has a conditional probability distribution. The conditional probability tables (CPTs) assigned to the nodes in the network denote conditional dependencies and are used to express the probability of each node

given the condition of its parent. Based on the conditional independence and chain rule, the joint probability distribution of a set of variables θ = {X1, X2… Xn} can be determined by:

$$P(\theta) = \prod_{i=1}^{n} P\big(X_i \mid Pa(X_i)\big) \qquad (1)$$

where $Pa(X_i)$ is the parent set of X_i.

The BN approach is based on the Bayes theorem to update the prior occurrence (or failure) probability of events given new evidence E in a probabilistic framework including the theory of subjective probability, which provides the posterior distribution. Hence, the general continuous form of the Bayes theorem is given by [24]:

$$P(\theta \mid E) = \frac{p(E \mid \theta)P(\theta)}{\int_{\Theta} p(E \mid \theta)P(\theta)d\theta} \qquad (2)$$

where P(θ|E) is the posterior distribution (θ can be a vector of parameters), P(θ) is the prior distribution of θ, P(θ|E) is the likelihood function, so the observed data enters via this aleatory model and *E* can be a set of observations.

In the discrete case, the Bayes decision rule is unchanged. The integrals are replaced by sums of the conditional probabilities for all possible values of E in the discrete distribution [8, 9, 25]:

$$P(\theta \mid \mathrm{E}) = \frac{P(E,\theta)}{\sum_{\theta} P(E,\theta)} \qquad (3)$$

3.2. Series and Parallel Systems

From a reliability viewpoint, the system is assumed to be a series system if the failure of one component leads to system failure. On the other hand, if only one component suffices for the system to function, then the system is said to be parallel [16]. A graphical representation, by means of a BN, of a series or parallel system with two components (A, B) and one additional node (N) is shown in Fig. 2.
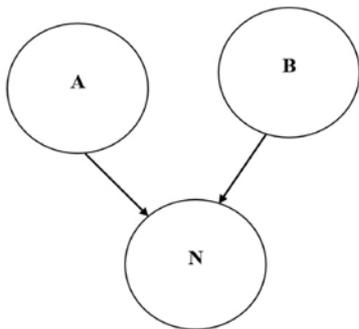

Fig. 2. Bayesian Network for two components

According to equation (1), the joint probability of the serial system with two components is:

$$P(N, A, B) = P(N \setminus A, B)P(A, B) \qquad (4)$$

Table 1. *CPT in the series system case with two components*

A	FAILED		RELIABLE	
B	FAILED	RELIABLE	FAILED	RELIABLE
FAILED	1	1	1	0
RELIABLE	0	0	0	1

The elements of the CPT P(N\(A,B)) are the combination of the parent nodes states, such as **A** and **B** failed, **A** failed and **B** is reliable, **A** is reliable and **B** failed and **A** and **B** are reliable. The CPT corresponding to the series system case is given in Table 1. In the parallel case, only the CPT is modified, as shown in Table 2.

Table 2. *CPT in the parallel system case with two components*

A	FAILED		RELIABLE	
B	FAILED	RELIABLE	FAILED	RELIABLE
FAILED	1	0	0	0
RELIABLE	0	1	1	1

3.3. Complex combination of series-parallel system configuration

In order to illustrate the advantages of using BN, the schematic reliability block diagram in Fig. 3 [5] is considered. First, the component C5 is chosen to simplify the solution. The system is divided into two subsystems shown in Fig. 3b and 3c—one when C5 is considered good and another where C5 has failed. Then, the selection of component C1 to be considered good or bad produces the two subsystems shown in Fig. 3d and 3e. In the case of Fig. 3d, components C2 and C3 do not appear because when C1 is good, the signal reaches C4 irrespective of whether C2 and C3 are good or bad; therefore, they become irrelevant.
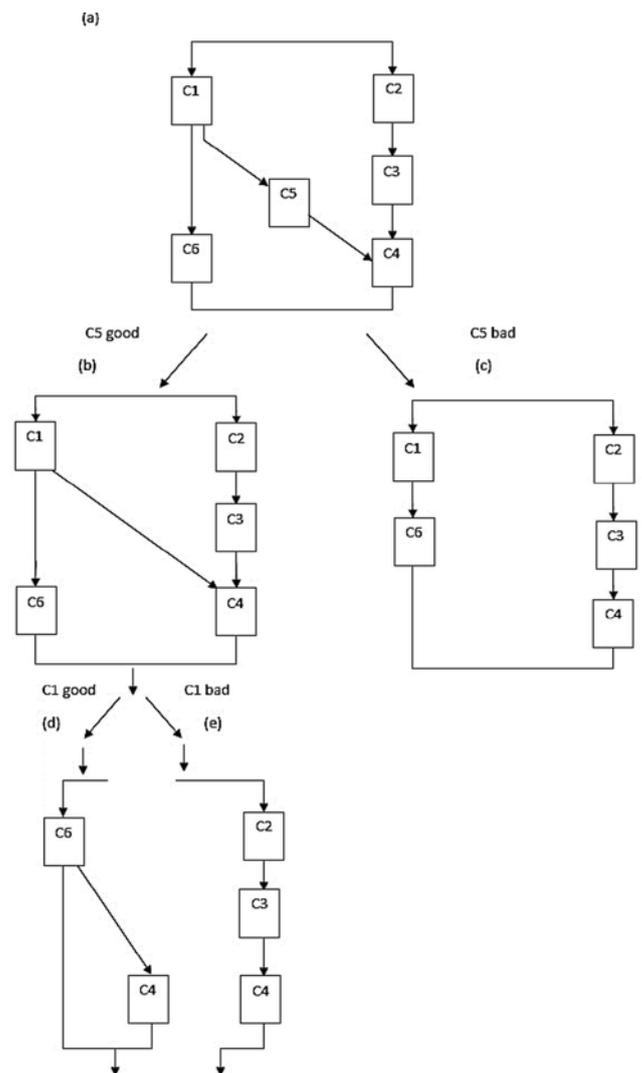

Fig. 3. Reliability diagram of illustrative example

-The system reliability can be deduced as follows:

- $R_s = R_s\left(if\ C_5\ is\ good\right)*R_{c5} + R_s\left(if\ C_5\ is\ bad\right)*\left(1-R_{C5}\right)$

- $R_s\left(if\ C_5 bad\right) = 1-\left(1-R_{C2}*R_{C3}*R_{C4}\right)\left(1-R_{C1}*R_{C6}\right)$

- $R_s = R_s\left(if\ C_5\ is\ good\right) = R_s\left(is\ good\ C_1\right)*R_{C1} + R_s\left(if\ C_1\ is\ bad\right)*\left(1-R_{C1}\right)$

- $R_s\left(is\ good\ C_1\right)*R_{C1} = \left[1-\left(1-R_{C6}\right)\left(1-R_{C4}\right)\right]*R_{C1}$

- $R_s\left(if\ C_1\ is\ bad\right)*\left(1-R_{C1}\right) = \left(R_{C2}*R_{C3}*R_{C4}\right)*\left(1-R_{C1}\right)$

-Substituting gives:

$$R_s = \left[1-\left(1-R_{C6}\right)\left(1-R_{C4}\right)*R_{C1} + \left(R_{C2}*R_{C3}*R_{C4}\right)*\left(1-R_{C1}\right)\ \right]*R_{c5}$$
$$+\left[1-\left(1-R_{C2}*R_{C3}*R_{C4}\right)\left(1-R_{C1}*R_{C6}\right)\right]*\left(1-R_{C5}\right)$$

- If each component has reliability as follows:

$C_1 = 0.7, C_2 = 0.8, C_3 = 0.9, C_4 = 0.6, C_5 = 0.55\ and\ C_6 = 0.7$.

- Substituting numerical values in the last equation gives:

$$R_S = 0.72972\ \ and\ \ F_S = 0.27028$$

The preceding method is difficult; thus, by using a BN approach the solution is simplified so the system reliability can be obtained from a single network, as shown in Fig. 4.
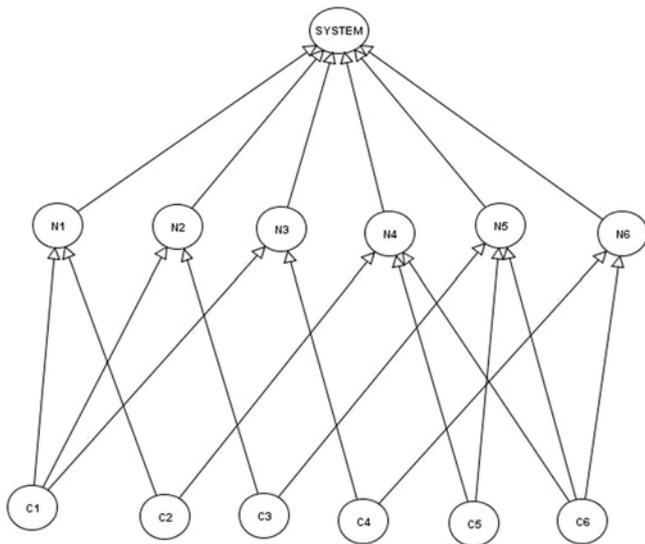

Fig.4. Bayesian network of the illustrative example

It is notable that the results obtained from the numerical simulation are identical to those obtained from the mathematical calculations.

3.4. Interaction between electrical network and STATCOM

The reactive energy flow in distribution networks has significant technical and economic consequences. In other words, when the reactive power drawn by consumers is too high compared to the active power, the increase in the electrical network current leads to overloads at power transformers, heating in power cables, significant voltage drops and additional losses. Therefore, it is necessary to produce reactive energy at levels as close as possible to the loads to avoid its transmission to the network. This is called reactive energy compensation. In practice, to avoid oversizing the installations and failure risks, the energy distributor financially penalizes reactive energy consumers from a certain threshold set at φ [18, 23] where tan φ is a useful intervention threshold to improve the electrical installation from which

there is a failure of the Electrical Networks–STATCOM system (Fig. 5). The failure system state is then given as:

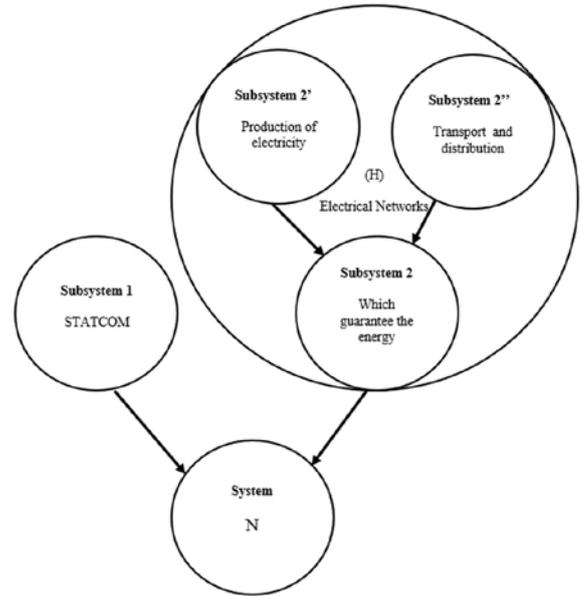$$\frac{Reactive\ power}{Active\ power} \geq \tan\varphi \tag{5}$$

Fig. 5. the Electrical Networks-STATCOM coupling

In reliability analysis, it is necessary to define a limit state function (also known as a performance function) that expresses the condition of the system safety or system failure equation [37]. Therefore, the limit state function $G(x_i)$ corresponds to the safety margin and is defined as follows:

$$G = \tan\varphi \cdot P - Q \tag{6}$$

This margin is defined such that $G(x_j) > 0$ indicates safety and $G(x_j) \leq 0$ corresponds to conventional failure; where x_j are the random variables in the system. In this expression, P is the active power load, Q is the reactive power load and tan φ is a threshold fixed by the energy distributor (φ expresses the phase of voltage relative to current). In the present work, the First Order Reliability Method, known as FORM [10], is programmed and applied to compute the reliability indexes and failure probability. FORM method define reliability index β as the minimum distance between the origin of the space and the failure domain in the equivalent Gaussian space u_i, where β is evaluated by solving the constrained optimization problem:

$$\beta = minimize\ \sqrt{\sum_i u_i^2}\ \ subjected\ to\ \ G(x_j) \leq 0 \tag{7}$$

where, $u_i = T_i(x_j)$ is the basic random variables vector in the standard normal space obtained by appropriate probabilistic transformation $T_i(x_j)$, and $G(x_j)$ represents the failure surface; in the standard normal space, it takes the form $G(T_j(u_i))$. In First Order Reliability Methods (Form), the failure probability P_f is calculated by:

$$P_f = P\left[G(X) \leq 0\right] = \Phi\left(-\beta\right) \tag{8}$$

where, P [G(X)≤0] is the probability operator and Φ (-β) is the cumulative Gaussian probability function. Due to electrical system complicity, the failure probability mentioned in this last equation (eq.8) is used to express the conditional probability of failure (CPf), in order to evaluate the CPT (table 3) of the BN node (fig. 5).

Table 3. *Conditional probability table of the node N in fig.5*

STATCOM	Failed		Reliable	
H	Failed	Reliable	Failed	Reliable
Failed	1	Cpf	1	Cpf
Reliable	0	1-Cpf	0	1-Cpf

The key idea presented in the previous statement is performing a logical arrangement of events to quantify the dependencies [32] between subsystem 1 (STATCOM) and subsystem 2 that guarantee the energy (H). The logical arrangement leads to different system states (reliable or failed) with respect to the limit state function in equation (6). Therefore, several situations can be considered. If the electrical network (H) fails, the obtained situation is a system shutdown regardless of the STATCOM situation (failed or reliable). On the other hand, if the electrical network (H) is reliable, the CPf has to be computed according to equation (8).

By translating the probabilistic dependencies among the variables into graphical models [30], the BN tool provides a comprehensible and modular framework for representing this complex electrical system. The methodology for the system reliability assessment is shown in Fig. 6. Because of their relevance to real-world applications, this adapted Bayesian approach is applied in the following section to a real case at the Algerian Company of Steel Industry (SIDER).
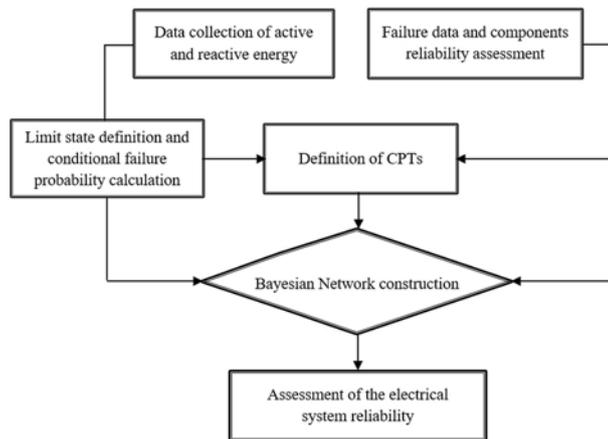

Fig. 6. Bayesian approach for the electrical system reliability assessment

4. Industrial application

The studied system is a high voltage (HV) electrical system consisting of electrical equipments which are presented in Table 4 and the network configuration is illustrated in (Fig. 7). In this part, an illustrative study to evaluate the reliability of the electrical system is demonstrated. It was started by finding a model composed from two subsystems STATCOM and electrical network. As a result, the complexity of the system can be classified in terms of configuration and operation. Finally, the STATCOM effect on the system reliability has been also studied.

In the following sections, the numerical analysis is carried out as following:
- Failure data and individual electrical components reliability;
- Electrical energy consumption and System Modeling by Bayesian Networks
- Assessment of the electrical system reliability with and without STATCOM
- Estimation of system reliability for three STATCOM configurations

4.1. Failure data and individual electrical components reliability

Based on the operational experience feedback data available from the Algerian Company of Steel Industry, lifetime distributions for different components of the electrical system have been estimated. The first analysis consists of extracting the times to failure for each component in order to constitute the samples, which are then fitted by a two-parameter Weibull model [15]. This statistical model was chosen because of its flexibility that allows, with a minimum of only five failures [43], correctly and effectively adjusting all kinds of operational or experimental results obtained during periods of youth, adulthood and aging (i.e., early failure, constant failure and wear-out failure, respectively). Thus, the reliability of individual electrical components as a function of service time (t) is given by:

$$R_i(t) = 1 - F_i(t) = \exp\left[-\left(\frac{t}{\eta_i}\right)^{\beta_i}\right] \qquad (9)$$

B_i and η_i are, respectively, the shape and scale parameters of the Weibull distribution for each electrical component i. The Weibull parameter estimation is obtained using MATLAB, and the estimation results are summarized in Table 5.

4.2. Electrical energy consumption and System Modeling by Bayesian Networks

The collected company data used in this work are from 2017. Using a recording PC, an example of the electrical system operation without and with STATCOM is presented, and the different results are illustrated in Fig. 8a and 8b at 10 h 33 m and 10 h 38 m, respectively.
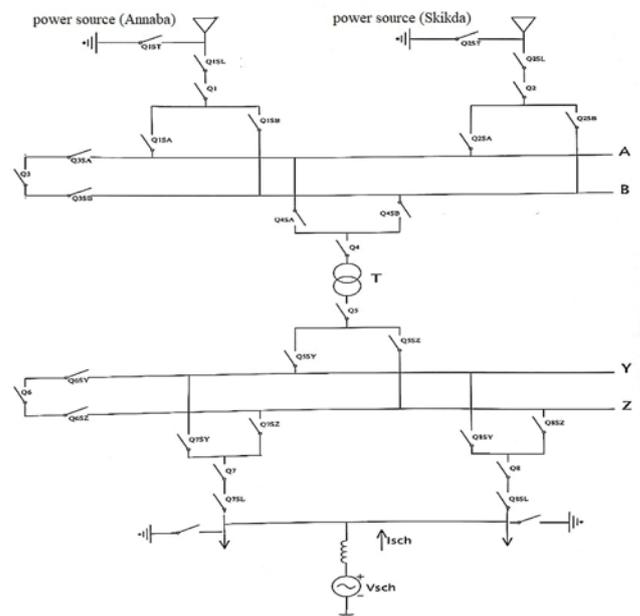

Fig. 7. Electrical schematic diagram of (HV) in (CRM) unity

Table 4. *Presentation of system electrical equipments (HV)*

Component (HV)	Code
HV Circuit breaker	$(Q_1, Q_2, Q_3, Q_4, Q_5, Q_6, Q_7, Q_8)$
Step down transformer 220kv to 60kv	T
Static synchronous compensator	STATCOM
HV Switch-disconnectors	$(Q_1SA, Q_1SB, Q_2SA, Q_2SB, Q_8SY, Q_8SZ, Q_4SA, Q_4SB, Q_5SY, Q_5SZ, Q_7SY, Q_7SZ, Q3SA, Q_3SB, Q_6SY, Q_6SZ)$
Lien disconnectors	$(Q_1SL, Q_2SL, Q_7SL, Q_8SL)$

Table 5.   Weibull parameters of the system components

Component	Code	Sample size	Shape Parameter β_i	Scale Parameter η_i
	Q1	10	0.871	9.631
	Q2	8	0.445	7.515
	Q3	9	0.715	5.312
HV Circuit breaker	Q4	12	1.178	11.404
	Q5	11	0.993	6.271
	Q6	10	0.755	5.545
	Q7	13	1.224	8.653
	Q8	13	1.117	6.116
Step down transformer 220kv to 60kv	T	15	1.230	7.775
Static synchronous compensator	STATCOM	14	1.036	3.861
	Q1SL	13	1.192	4.414
Lien disconnectors	Q2SL	10	0.746	10.913
	Q7SL	9	0.726	5.829
	Q8SL	11	0.732	5.452
	Q1SA	9	0.617	8.714
	Q1SB	9	0.992	6.672
	Q2SA	11	0.726	1.911
	Q2SB	12	0.776	9.355
	Q3SA	12	0.993	6.271
	Q3SB	14	1.004	9.718
	Q4SA	11	0.737	7.120
	Q4SB	10	0.687	6.110
HV Switch-disconnectors	Q5SY	11	0.758	6.645
	Q5SZ	12	0.763	6.436
	Q6SY	13	0.769	6.302
	Q6SZ	12	0.676	5.806
	Q7SY	11	0.732	5.452
	Q7SZ	11	0.670	4.250
	Q8SY	14	1.420	10.783
	Q8SZ	12	0.723	6.031

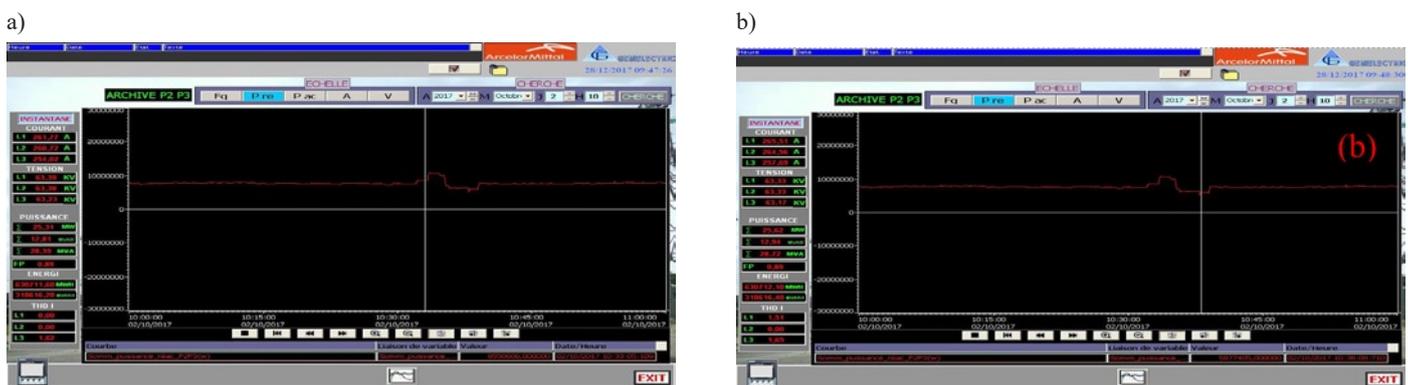a)   b)

Fig. 8. Electrical system operation without and with STATCOM (a and b, respectively)

First, it was decided to operate the installation without STATCOM, which allowed us to record a reactive power value Q1 = 8.54 MVAR for a given time 10 h 33 m, as shown in Fig. 8a. When using STATCOM, a reactive power value Q2 = 5.9 MVAR was recorded at a given time 10 h 38 m, as shown in Fig. 8b. It can be seen that, for the same load, a significant reactive power variation has been observed, which is explained by the main effect of the STATCOM on the installation function. Fitting data to a lognormal distribution for a reference meas-

urement period of one year leads to the results in Fig. 9, where the reactive power variation is described for cases with and without STATCOM. Fitting a distribution curve of the system with STATCOM (Fig. 9a) shows a nearly symmetric distribution with a mode, median and mean of 5.48, 5.50 and 5.52, respectively. The curve distribution for the system without STATCOM (Fig. 9b) shows a positively skewed distribution with a mode of 6.40, a median of 9.18 and a mean of 11.31. The scale and standard deviation with STATCOM are 0.07 and
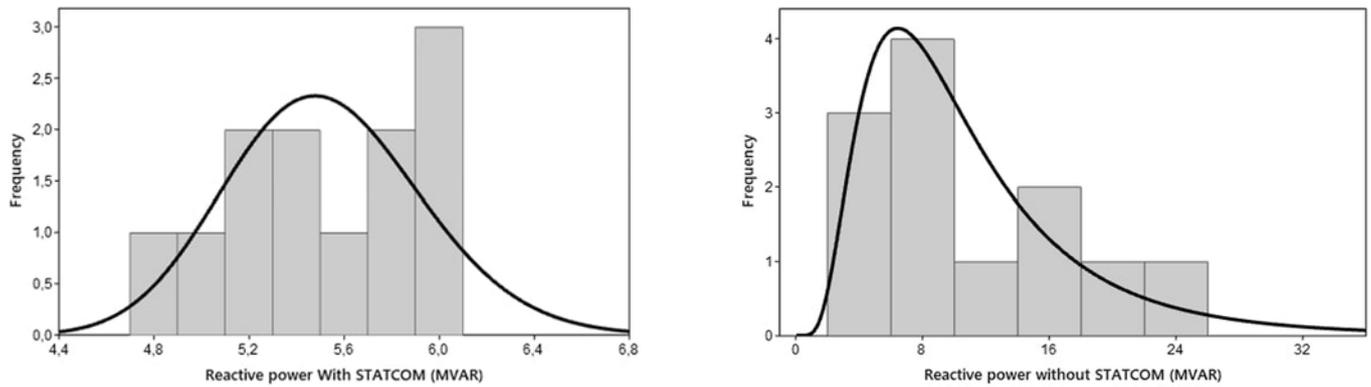
Fig. 9. Probability density function of the reactive power with and without STATCOM (a and b, respectively).

Table 6.   Input data of the electrical energy consumption

Variable	Symbol	Mean value (MVAR)		Coefficient of variation	
		Without STAT-COM	With STATCOM	Without STAT-COM	With STATCOM
Active power	P	18.57	19	0.14	0.13
Reactive power	Q	11.31	5.52	0.72	0.08
Intervention threshold	tan φ	0.5	0.5	-	-

0.42, respectively, and those without STATCOM are 0.64 and 8.15, respectively. The results from both histograms imply that the system is positively influenced by the presence of STATCOM.Fitting data to a lognormal distribution, for a reference measurement period of one year leading to the results in(Fig.9), where the reactive power variation is described for cases with and without STATCOM. Fitting distribution curve of system with STATCOM (Fig.9 (a)), show a nearly symmetric distribution with the respectively value of mode, median and mean 5.48, 5.50, 5.52. The curve distribution for the system without STATCOM (Fig.9 (b)) show a positively skewed with a mode of 6.40, median of 9.18 and mean of 11.31. The scale and the standard deviation with STATCOM are 0.07 and 0.42, respectively, that showed very low ones than without STATCOM who have 0.64 and 8.15. The reveal results observed from both histograms implies that system is influenced by the presence of STATCOM in a positive way.

The main model objective is to quantify the impact of the STATCOM on complex electrical system reliability. The system components' interactions as well as probabilistic dependencies between the system and STATCOM are translated into graphical models. As can be seen in Fig. 5, the electrical system is divided into two subsystems – the first ensuring the compensation of reactive energy (STATCOM) and the second guaranteeing the energy – where each subsystem is represented by a node in the BN and is related to one node (N) in order to quantify the dependencies between them. In Algeria, the intervention threshold tan φ is fixed at 0.5 [12], which is equivalent to keeping the power factor at approximately 0.9. In other words, the ratio of reactive to active power should not exceed 0.5, and exceeding this value results in a financial penalty; so, the consumer is responsible for controlling their own reactive power load. The corresponding limit state function defined by equation (6) consequently takes the following form:

$$G=0.5P-Q \qquad (10)$$

The test data for the electrical energy consumption are introduced in the probabilistic model for computing the conditional probability of failure according to equation (8), where the input data are provided in Table 6.

The other part of BN consists of a complex combination of series-parallel nodes representing variable interactions expressed in arcs between variables; nevertheless, arcs are not allowed to form a closed loop. From the BN process, a model for determining whole system reliability is developed. The designed model can forecast, diagnose and make decisions by combining data and knowledge about complex causal dependencies in real industrial cases. The overall structure of the BN is constructed according to the methodology developed in Section 3. Fig. 10 represents the nodes of the electrical system components, and the nodes allow the quantification of the interdependencies between these components as well as the relationship between the STATCOM and the electrical network.
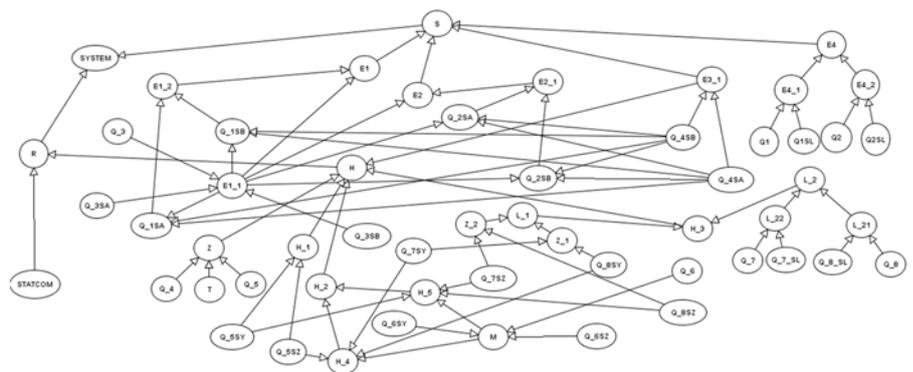

Fig. 10. Bayesian network of the electrical system

4.4. Assessment of the electrical system reliability without and with synchronous static compensator (STATCOM)

The reliability assessment of the electrical system, taking into account the effect of STATCOM, is now considered and carried out by coupling of the models above. Therefore, for a reference lifetime of
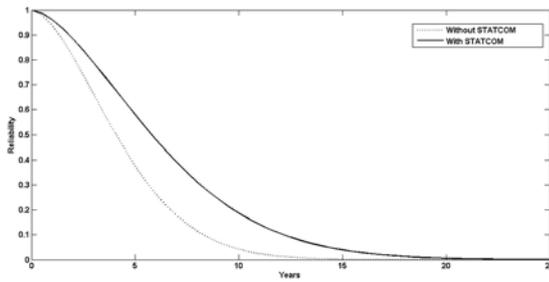
Fig. 11. Electrical system reliability without and with STATCOM

25 years, the Bayesian inference result reported in Fig. 11 compares reliability evolution as a function of the electrical system service lifetime for both system cases, with and without STATCOM (solid and dashed lines, respectively), in order to show this effect. As expected, a similar trend arises for both cases: reliability decreases with electrical system age and failure probability correspondingly increases. However, a significant reliability decrease is noted without STATCOM. As an example, the reliability without STATCOM after five years of system operation was found to be 39%, which is considered a low reliability especially in the early years of operation. During the real life of the studied electrical system, this ratio decreases in a tangible way. The reliability after 10 years of service is about 5%, and the reliability from 15 to 25 years is close to 0%. However, the obtained result of electrical system reliability with STATCOM shows good improvements in reliability; after five years of service, the reliability is about 60%. During the electrical system's real lifetime, the reliability rate is reduced. At 10, 15 and 20 years, the respective reliabilities are 19%, 5% and 1%. So, the obtained results confirm that ignoring the reactive energy compensation leads to significant impacts on system failure probability. For these reasons, it is necessary to optimize the electrical system design, and reactive power transport should be limited in order to use the network to its maximum capacity – in other words, producing reactive power where it is consumed. In conclusion, these curves supply the designer and the maintenance service with a realistic image of the electrical system's risk of failure at various lifetime instances with regard to reactive energy compensation.

4.5. Estimation of system reliability for three STATCOM configurations

According to three configurations of the STATCOM within the electrical network (series, parallel and the proposed configuration), Fig. 12 depicts the reliability evolution as a function of the elapsed electrical system life for the different configurations and compares them with each other. In practice, the series and parallel positions are not realistic, but they were considered in our study to be sure that the proposed model results differ from the series and parallel positions' results and that the proposed model can be recommended. As well, the STATCOM should be connected at the appropriate position in order to properly monitor the system. However, the system reliability will be difficult and complicated to determine. An adapted Bayesian approach is used to cope with this constraint and define the reliability of this complex electrical system. Fig. 12 shows that the three considered configurations have almost the same trends, with a decrease in reliability as a function of time, and the curve obtained by the proposed method represents neither the configuration in series nor the configuration in parallel. In Fig. 12, the comparison of the reliability curves shows that considering the STATCOM in series with the electrical network leads to over-penalizing and can prematurely stop the electrical system. For example, at five years of service, the system reliability is estimated at close to 0.40 – much lower than the reliability estimate of 0.60 in the proposed model. Furthermore, considering the STATCOM in parallel with the electrical network leads to an overestimated electrical system reliability and may lead to incorrect decisions in a

risk-associated situation. As an example, after five years of service, the system reliability in parallel is equal to 0.90 – much higher than the reliability estimates of 0.60 in the proposed model. According to the above results, it can be concluded that the parallel and series configurations can lead to errors in the evaluation of the electrical system's reliability.
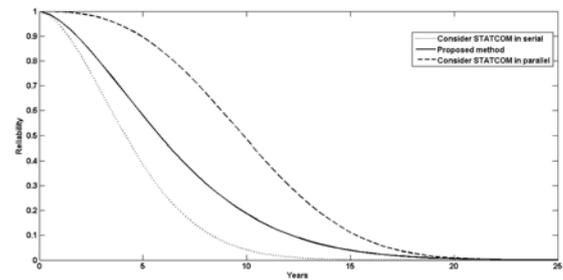

Fig. 12. Electrical system reliability according to the three configurations

5. Conclusion

This study presents a practical model to assess an electrical system's reliability using BN, which has emerged as one of the most promising modeling and analysis frameworks in terms of risk control and reliability. The use of BN makes it possible to notice the effect of a STATCOM reactive energy compensator on the electrical network and quantify the dependencies between the STATCOM and the electrical network constituting the entire system. From the study results, the following main conclusions can be summarized:

– The study of a system's lognormal reactive energy distribution without and with STATCOM shows that electrical system stability with STATCOM is better than it is without STATCOM. It has also been proven that the performance of an electrical system with a compensator is better than that without a compensator, and a positive influence on reliability has been observed.
– The connection of STATCOM is important for improving the system's overall reliability performance; moreover, the parallel and series configurations can lead to erroneous evaluations of the system reliability, which can lead to an insecure situation (i.e., false confidence interval).
– The developed model can help specialists carry out surveys and can provide valuable information to decision makers for improving system reliability performance.

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