Formal Verification of Single Dual Setting Overcurrent Directional Relay Based Line Protection Logic for Smart Grids

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***Abstract*—Power system protection plays a very significant role in the reliable operation of the power grid, by safeguarding the personnel, equipment, and property against any undesirable events. These protection systems are traditionally analyzed using computer simulation and physical testing. However, the sampling-based nature of these analysis techniques does not allow us to cover all the possible scenarios and thus the resulting protection systems may not guarantee complete protection. This fact can lead to partial or complete power loss/blackouts, which can have devastating consequences. Formal verification methods have been successfully used to overcome the incomplete analysis issues in many domains of engineering. We believe that their introduction in the analysis of protection systems can lead to more reliable power grid operations. With this motivation, we propose to formally verify the correctness and reliability of the conventional and dual setting directional overcurrent relays. In this regard, we propose the development of the generic Markovian models of the conventional and dual setting directional overcurrent relays. To illustrate the effectiveness of the developed models a simple three bus distribution system network is analyzed to formally verify the efficiency and reliability of these models using PRISM, which is a probabilistic model checking tool. Furthermore, the failure and success probabilities of isolation of the faulty section are also determined.**

***Index Terms*—Dual setting directional overcurrent relay, Formal methods, Probabilistic model checking.**

I. Introduction

In recent years, the idea of distributed generators (DGs) is being widely discussed, developed, and adopted due to evolution in the smart grid and its variety of applications. DGs integration introduced many issues like the varying fault current levels, bidirectional power flow issues, blinding of protection due to external fault current infeed, and weak infeed phenomenon, etc. The bidirectional power flow issue causes sympathetic tripping which can be addressed using directional overcurrent relays (DOCRs) [1], [2]. With ever-progressing technological progression, multi-functional numerical relays are now considered as the substitute for conventional DOCRs. Many protection functions can be implemented using these relays like distance protection, etc. The fault clearing time of the system is directly proportional to the number of the installed relays because the operate-time delay settings must consider the necessary selectivity. Such systems are more complex and become prone to high fault rates. To cater to such issues, dual-setting DOCRs were introduced. A single dual setting relay can operate in both forward (primary) and reverse (backup) directions simultaneously thus decreasing the total fault clearing time. The same approach was proposed to protect the DGs integrated meshed distribution system [1]. Moreover, a more reliable and economic protection algorithm has been proposed by utilizing optimal integration of conventional and the dual setting DOCRs [3]. Similarly, the hybrid integration of conventional and dual setting DOCRs was implemented in optimal typologies to decrease the count of relays and current transformers (CTs) used for the protection of lines in the IEEE 14 bus distribution system [4]. Thus, it was concluded that the mixed integration of dual setting DOCRs and conventional relays not only reduced the relays operation times but also reduced the operational CTs and relays count.

Since the reliability of the whole power system is very much dependent on the reliability of its protection system, a rigorous statistical analysis of the behavior of the protection system is a great contribution to its evaluation. The evaluation will provide important indications to compare one protection scheme against others, or even to trim the relay protection settings for the same scheme. This, in turn, will contribute to optimize the power system protection paradigm, which is the compromise between dependability and security: faster elimination of the power system faults and less unwanted operations, with clear benefits on the continuity of service of the power system. Traditionally, numerical and simulation-based methods are utilized to analyze the reliability of the protection systems of smart grids [5], [6]. However, their results cannot be termed as complete and accurate. A few major reasons causing the inaccuracies in the results is the limited number of use cases that can be assessed with this approach because they require the use of complex tests systems like power system network simulations, voltage, and current amplifiers, protection relays, and qualified personnel to perform the tests

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and evaluate the test results. In few words, the properties are assessed through a sampling-based approach, and thus all the possible scenarios are not considered. Therefore, during these analyses, some important situations may be left undetected. These situations could lead to disastrous consequences on the operations of smart grids due to their safety-critical nature. For instance, the famous blackout in the United States and Canada back in 2003, was caused due to inaccuracy in the analysis of the system which affected almost 55 million people [7]. So, accurate analysis of protection algorithms is required.

Our approach is based on the use of a formal method [8]. Inputs required for the simulator are the system description and the set of possible test vectors based on which the simulator analyzes the given system and provides the results. The inputs required by the formal verification tools are a mathematical model of the system and a set of associated properties. Based on the given properties, the formal verification tool exhaustively traverses the entire state space of the system model and provides the verification results. So if the system model and the properties are defined accurately, the verification results can be termed accurate. The formal verification methods are widely used in verifying systems used in the safety-critical domains to identify and rectify the bugs, which may be left undetected otherwise. The probabilistic model checking, which is a formal analysis technique for Markovian models, has been used to estimate the probability of failure of transmission network by utilizing the data measured by phasor measurement units (PMUs) as a backup protection system [9]. Moreover, the integrated model of fault detection, isolation, and recovery (FDIR) with power line carrier (PLC) and wireless communication networks have also been verified using the probabilistic model checker PRISM [10]. Similarly, the reliability analysis of the relay-protected component has been done using model checking [11], [12]. As the conventional DOCRs and dual setting DOCRs are commonly used to protect DGs integrated distribution networks, the reliability of these relays has an impact on the reliability of the entire distribution network. Therefore, the accurate reliability analysis of these relays is very important to determine the reliability of the entire network. The main concept behind the reliability analysis of these relays is to first build the mathematical models of these relays and then to find the associated probabilities with different parameters of interest like relay failure/operation etc.

To the best of our knowledge, so far, no prior work has been done to test the reliability of conventional and dual setting DOCRs based protective systems of smart grids using formal verification in general and probabilistic verification using PRISM in particular. In this paper, we propose to utilize the probabilistic model checker PRISM to investigate the reliability of the conventional and dual setting-based protection system with backup protection for smart grids. Apart from being a vital step in the analysis of smart grids, reliability analysis can also be used to reduce the load from the whole grid and can be effective in setting up system maintenance to guarantee a cost-effective, secure, and reliable operation accordingly.

A. Our Novel Contribution

Our foremost contribution in this paper is to develop the generic discrete-time Markovian models (DTMC) of the protection components, such as conventional DOCRs and dual-setting DOCRs. These models along with the other component models can, in turn, be used to build the DTMC model of the entire protection system. This overall DTMC model can be used with the probabilistic model checker to formally verify different performance and functional properties that can give very useful insights into the protection system operation. For instance, the information of the probability of the success or failure of primary or backup protection is very important for the protection system engineers. We have identified some of the probabilistic properties for the probabilistic verification of single and dual-setting DOCRs based protection systems. These properties include:

- Success/failure probability of isolation of faulty section (Dependability)
- Probability of successful operation of primary or backup relays (Dependability)
- Probability of failure of primary or backup relays (Dependability)
- Probability of complete failure of protection system for conventional and mixed relays deployment (Dependability)

To demonstrate the effectiveness of the proposed models we have chosen a three bus system with six relays and verified the above-mentioned properties and compared their results considering different relay deployment scenarios.

II. Preliminaries

A. Probabilistic Model Checking and PRISM

Model checking is a formal verification technique primarily used to verify reactive systems [13], i.e., the systems that exhibit time and environment-dependent behavior. A model checking tool accepts the mathematical model of the system that is captured in the form of a finite state machine and the set of specific properties, which are specified in the temporal logic. The model checker rigorously verifies the system model against the specified properties and verifies if the given system model holds the required properties. In the case of failing properties, it provides corresponding counterexamples. Probabilistic model checking is an extension of the traditional model checking techniques [13] that allows the analysis of systems that exhibits random behavior. PRISM is a widely used probabilistic model checking tool. The systems to be verified are first presented as a variant of the Markov chains, i.e., DTMCs, Continuous-time Markov chains (CTMCs), or Markov Decision process (MDPs) [14]. The specification languages available for the PRISM are Linear temporal logic (LTL), Computational tree logic (CTL), and probabilistic computational tree logic (PCTL) [13].

B. Conventional DOCRs and Dual Setting DOCRs

In the case of conventional DOCRs, each relay can operate as primary as well as backup. Whenever the relay senses a fault current in its forward direction, its over-current element is enabled and if its value is higher than the prescribed level then the relay starts operates and trips its associated circuit breaker. Whereas, if the current direction is not forward then the relay does not start (picks-up) and neither operates (trips). The relays closest to the fault point act as primary relays and the relays located far from the fault point act as a remote backup and operate when the associated primary relay fails.

In the case of dual setting relays, each relay can operate in the forward direction as well as in the reverse direction depending on the current direction. Whenever the relay senses a fault current in its forward direction, its over-current element is enabled and if its value is high, then the relay operates and trips its associated breaker. If the current direction is reversed, the relay is meant to operate as a remote backup relay for the other feeders, which are mainly protected by the detection of the fault current in the forward direction. To ensure the proper coordination between primary and backup relays, a time delay is introduced between the operation in the reverse direction of a backup reverse zone and the operation in the forward direction of a main forward zone.

III. Proposed Methodology

The proposed methodology is illustrated in Fig .1. The first step is to develop a DTMC model of the given system. The evolution probabilities of this model can be determined based on the total number of protected components and their failure probabilities, which can in turn be obtained via statistical analysis. In the next step, we formally specify and verify probabilistic properties associated with the functionality and performance of the overall system by integrating the individual components in the PRISM model checker.

In this work, the first step was to build the DTMC models of the conventional and dual setting DOCRs. In the next step, these modules are integrated to develop the test system model. Next, we specify the probabilistic properties associated with the performance of the model, like success/failure probabilities of primary relays, success/failure of backup relays, and success/failure of fault zone isolation. Once, the DTMC model is developed, then both the model and the specified probabilistic properties expressed in the form of PCTL are fed to the PRISM model checker for rigorous verification. Finally, the PRISM exhaustively traverses the entire state space of the system and provides the associated success or failure probabilities.

A. DTMC Models

1) DTMC Model of Conventional DOCRs: The state-space of the conventional DOCR relay is shown in Fig. 2. All the variables used in the state space description are described in Table I. All the variables are initialized in the initial State 0 of the model. Smart grid is a numerical power system, and it has numerical relays which have self-supervision, if there is a problem, they detect it and can inform the user that they are faulty. So, they can be replaced quickly and the availability increases. There is also the possibility of wrong settings. The overcurrent threshold settings for these relays are not easy,

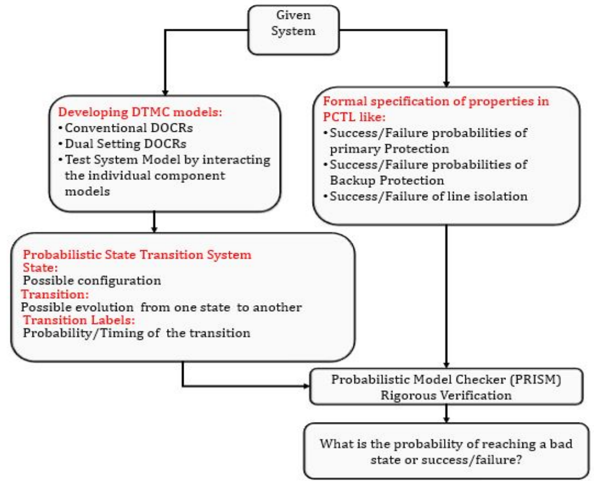


Fig. 1. Probabilistic Model Checking Methodology

because it depends on the fault current levels. So, they can fail hence, the probability of relay failure is also considered. For comparison purpose, it is varied from 0 to 1. The probability that the relay has an internal fault is also varied from 0 to 1 in our model. The state-wise description of the model is as follows:

- State 1: Relay has an internal fault
- State 2: Relay is not faulty
- State 3: Relay operates due to high current detected in the forward direction
- State 4: Relay does not operate due to some external fault
- State 5: If the relay is required to operate due to fault and it fails to operate then it moves to State 5 indicating that a backup is required

2) DTMC Model of Dual Setting DOCRs: The state-space representation of the dual setting DOCRs is shown in Fig. 3. All the variables are initialized in the initial State 0 of the model. The probability that the relay has an internal fault is taken as 0.1. The state-wise description of the model is as follows:

- St_r 1: Relay is not faulty
- St_r 2: Relay has an internal fault
- St_r 3: Relay operates as the primary relay due to high current detected in the forward direction
- St_r 4: Relay operates as the backup relay due to high current detected in the reverse direction
- St_r 7: Relay does not operate as no current detected in the forward/reverse direction
- St_r 8: If the relay is required to operate and due to any external fault it fails to operate, then it moves to State 10, indicating that backup is required

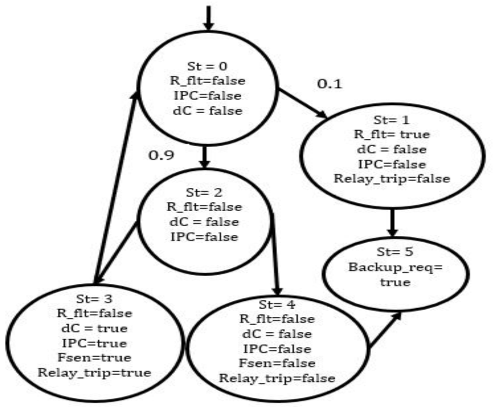


Fig. 2. The Conventional DOCR Model

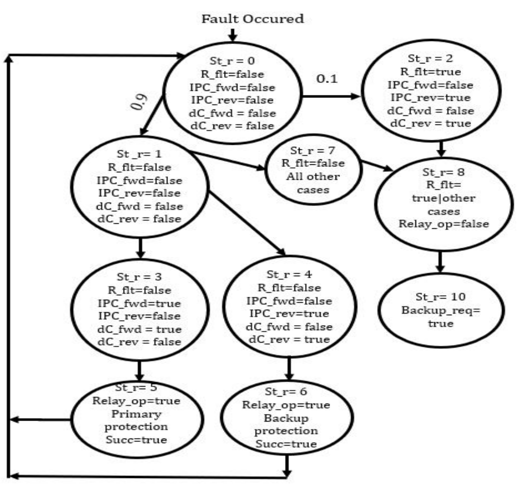


Fig. 3. The Dual setting DOCR Model

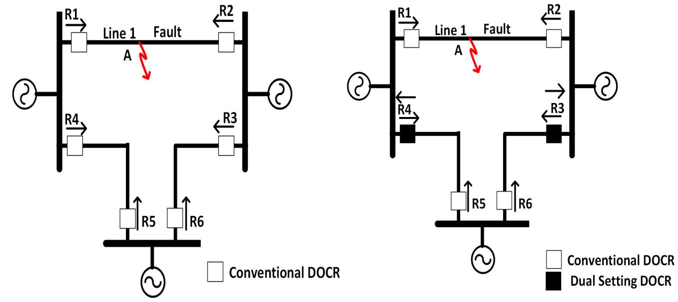
IV. Case Study

A. Test System Description

To formally verify the performance of the conventional and dual setting directional overcurrent relays, a simple three bus test system is considered. This system comprises three buses and six relays. We consider two cases as shown in Fig. 4. In the first case, deployment of all six conventional DOCRs is considered. Whereas, in the second case, some of the conventional DOCRs are replaced by the dual setting DOCRs. To analyze the performance of relays, a fault is assumed at the midpoint of Line 1 is protected by primary relays R1 and R2 and backup relays R5 and R6 in the conventional case. Both the primary and backup relays in this case are only capable of operating in one direction. Consider Fig. 4a, where Relays R1 and R2 act as primary relays for the fault at Line 1, whereas, Relays R5 and R6 act as backup protection. The DOCRs with dual settings have two different settings for forward and reverse operation. Consider the scenario shown in Fig. 4b, in which Relays R3 and R4 are equipped with dual settings, whereas, Relays R1, R2, R5, and R6 remain conventional. Relays R1 and R2 now provide primary protection for fault A on Line 1. The reverse direction of Relays R4 and R3 serve as backups for R1 and R2, respectively.

TABLE I
Meanings of Variables used in DTMC Models of DOCRs

Variables	Meanings
St/St_r	Relay states
IF	Fault current : No fault=false, Fault =true
R_flt	Relay faulty True/False
dC/dC_fwd/dC_rev	Current direction sensed by relay True(Forward/Reverse)
IPC/IPC_fwd/IPC_rev	Pickup current value of the relay True/False
Relay_trip/Relay_op	Relay operated or not: True/False



(a) (b)

Fig. 4. Relay deployment cases: (a) Conventional Configuration (b) Mixed Configuration

1) DTMC Model of Test System : A DTMC model of the simple three bus test system was developed by integrating the individual DTMCs of the relays while considering their concurrent operation. The generic state-space representation of the test system is shown in Fig. 5. This three bus system runs smoothly in the initial state if no fault occurs on the system. The probability for the occurrence of a line fault is assumed to be 0.1 on Line 1. A unique relay identity (Rid) value is assigned to each relay present on the network while considering its location concerning the fault point. For example, for the fault on Line 1 primary relays have Rid=0 and the first backup relays have Rid=1, similarly, if there is a second backup available then it's Rid=2 and so on.

Once, a fault occurs on the system in State y=1, considering the conventional configuration the primary and backup relays are activated with Rid=0, and Rid=1, respectively in State y=3. In the State y=4 if both the primary relays operate successfully then the fault zone is isolated and the system restores to the initial state y=0. If both the relays fail to operate then State y=5 and the backup protection is activated. A time delay of usually 0.2 to 0.5 secs is introduced between the primary and backup relays to ensure proper coordination. In this model, it is taken as 0.3 secs (it does not affect our analysis). If both the backup relays operated successfully then the system restores from State y=6 to y=0. otherwise, if the first backup fails and

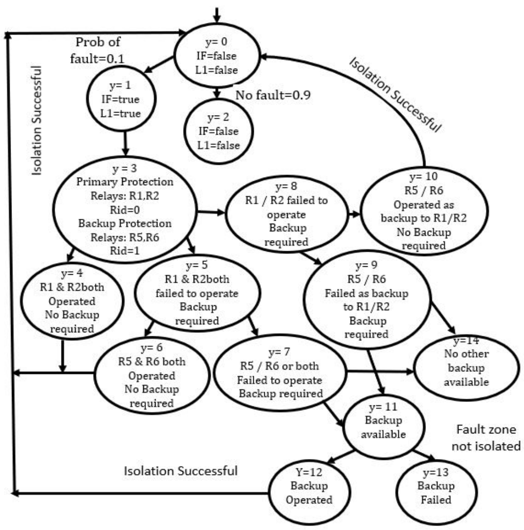


Fig. 5. Test System Model

another backup is available and operates successfully then the system restores from State y=12 to y=0. In case of backup failure, the system remains in the same state.

B. Probabilistic Properties

A set of probabilistic properties that are verified for the test system are depicted in II. A description for these properties can be given as follows: Line isolation property determines the probability that the required primary or backup relays have operated successfully or not. Similarly, if the State variables St and St_r have values 4 and 8, respectively, it means the corresponding relays failed to operate. if the State variables St and St_r have values 3 and 5 it means the corresponding relays have operated successfully.

C. Verification Results and Discussion

We have used PRISM 4.7 running on an intel core-i5 7200U CPU 2.71 GHz processor with 8 GB memory for the analysis.

1) Case I: Conventional DOCRs Deployment : In this case, relays R1 and R2 act as the primary relays, and R5 and R6 as the backup relays. The verification results obtained from PRISM are presented in Table III.The computational burden for the conducted case study is states are 5722 and the time taken for model construction is 0.225 s and the model checking time is 0.085 s. The results show that the chance of relays R1 and R2 operating together is 73%. Whereas, the probability that both the primary relays fail simultaneously is almost 2.1% and either one fails is approximately 12.39%, which shows that the probability of single relay failure is almost 10 times higher than the case when both relays fail simultaneously. Similarly, the probability of backup failure is 0.235%.

2) Case II: Mixed Deployment of Conventional and Dual Setting DOCRs: In this case, the relays R3, and R4 are replaced by the dual setting relays. Whereas the relays R1,

R2, R5, and R6 are kept as conventional DOCRS. For the fault on Line 1, the configuration of the relay as primary and backup is given in Table III. It can be observed that the relays R1 and R2 are acting as primary relays, and the reverse direction of the relays R4(rev) and R3(rev) are acting as the first backup to the relays R1 and R2, respectively. Moreover, this configuration also provides a secondary backup,i.e., conventional relays R5 and R6 act as backup if R4(rev), and R3(rev) fail to operate. The probabilistic verification results obtained for this case are presented in Table III. The results show that the probability that the first backup relays operate/fail simultaneously is 0.38% and 0.68%, respectively. The chances of a single backup relay failure are 7.09%. Similarly, the probability of backup failure is 0.0834% which corresponds to a reduction of 0.15% as compared to the conventional case.

From our analysis, it can be concluded that the deployment of mixed dual settings and conventional relays can improve the overall reliability of the protection system. But the optimal deployment of dual relays is very important to get the desired results. Additionally, an estimate of the success or failure of line isolation for the two cases is also given in Table IV. A comparison of results shows that in the case of conventional configuration, chances of successful line isolation are higher as compared to the mixed case. But the mixed relays deployment case is more reliable than the prior one.The number of states, in this case, are 57000 and the time taken for model construction is 1.454 s and model checking time is 0.304 s.

3) Case III: Impact of variation of probabilities on the properties : The previous results are obtained considering the fixed probability value of 0.1 for both the occurrence of a

TABLE II
PROBABILISTIC PROPERTIES FOR TEST CASE

Properties		PRISM Syntax
Line Isolation	Successful	P=? [F Line_ISO=true]
	Failure	P=? [F Line_ISO=false]
Successful Operation of Relays	Primary (Conv)	P=? [F (St=3 & St2=3]
	Backup (Conv)	P=? [F (St5=3 & St6=3]
	Backup(Dual)	P=? [F(St_r=6 & St_r3=6]
Failure of Relays	Primary (Conv)	P=? [F(St=4& St2=4)]
	Backup (Conv)	P=? [F(St5=4 & St6= 4)]
	Backup(Dual)	P=? [F(St=4 & St2= 4)& (St_r=8 & St_r3=8)]
Complete Failure	Conv case	P=? [F(St=4 & St2=4 & St5=4 & St6=4)]
	Mixed case	P=? [F(St=4 & St2=4 & St_r=8 & St_r4=8 & St5=4 & St6=4)]

TABLE III
PROBABILITY ESTIMATION RESULTS FOR THE CONVENTIONAL AND MIXED DOCRS

Conventional Configuration					
R1,R2 Operatd	R1,R2 Failed		R5,R6 Operated	R5,R6 Failed	
0.731	0.021		0.0123	0.00235	
R1 Failed R2 Operatd		R5 Operated (Backup)		R5 Failed (Backup)	
0.1239		0.0512		0.017	
R1 Operated R2 Failed		R6 Operated (Backup)		R6 Failed (Backup)	
0.1239		0.0583		0.0628	
Mixed Configuration					
R1,R2 Operatd	R1,R2 Failed	R3_rev, R4_rev Operated	R3_rev, R4_rev Failed	R5,R6Operated	R5,R6 Failed
0.731	0.021	0.00384	0.00689	0.004	0.000834
R1 Failed R2 Operatd	R4_rev Operated (Backup)	R4_rev Failed	R5 Operated	R5 Failed	
0.1239	0.0529	0.0709	0.0512	0.017	
R1 Operatd R2 Failed	R3_rev Operated (Backup)	R3_rev Failed	R6 Operated	R6 Failed	
0.1239	0.0529	0.0709	0.0307	0.0386	

fault and the relay failure. To analyze the impact of variation of probabilities on the results, we varied the probability of relay failure between 0 to 1 and verified some properties. A comparison of the impact of the relay failure on the complete protection failure for the conventional and mixed configurations is presented in Fig. 6. The results show that as the relay failure probability increases from 0 to 0.8 the reliability of the mixed configuration as compared to the conventional configuration increases from 0.15% to a peak value of 7.6%. If the relay failure probability is increased further the reliability starts decreasing. Moreover, the impact of variation of relay failure rate on line isolation success/failure rates is also depicted in Fig. 7.

TABLE IV
COMPARISON OF CONVENTIONAL AND MIXED CONFIGURATIONS

Configuration	Successful Isolation	Isolation Failure	Complete Failure
Conventional	0.813	0.187	0.00235
Mixed	0.892	0.105	0.000834

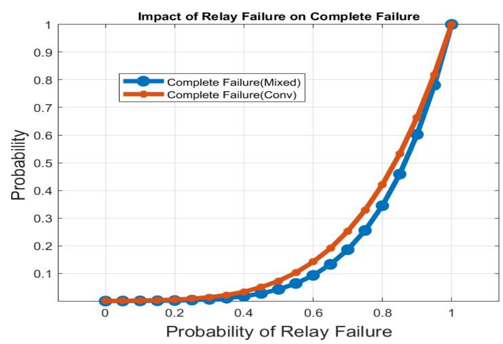


Fig. 6. Impact of Relay Failure on Complete Protection Failure

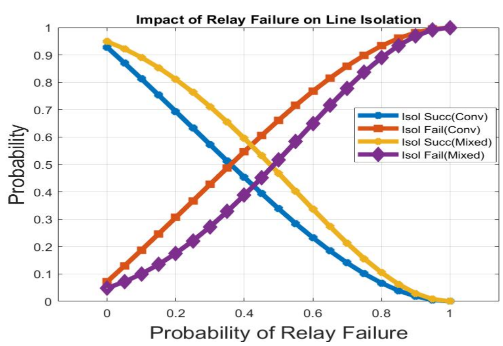


Fig. 7. Impact of Relay Failure on Line Isolation

V. CONCLUSION AND FUTURE WORK

This paper presents a formal performance analysis methodology, based on probabilistic model checking, for mixed traditional and dual setting DOCRs based protection system for single-point faults. The distinguishing feature of the proposed methodology is its rigorous nature compared to the sampling-based simulation. However, this work does not supplement HIL testing. It is demonstrated that using mixed traditional and dual setting DOCRs instead of just conventional relays improves the overall reliability of the protection system. As a result of this analysis, it can be concluded that the mixed deployment of conventional and dual setting-based DOCRs can be a possible solution to enhance the reliability of the protection system. However, the optimal placement of the dual setting relays is very crucial to obtain the best results. In the future, we intend to extend the analysis for more complex networks with multiple faults and different cases for the mixed relays deployment this would require the use of more optimized models for relays with more abstractions. We also plan to develop the generic Markovian models of the entire distribution network and protection system components, like, circuit breakers, transformers, and lines along with the formal specification and verification results of the functional and performance properties to provide more realistic analysis.

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