Modeling of Protective Relays for Transient Stability Analysis

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***Abstract*—This paper proposes a model for protective relays in dynamic simulations. The model consists of three layers: measurement, decision-making and actuator. This eyes-brain-muscle structure models the construction of a real-world relay and therefore allows easy involvement of accurate dynamics, such as measurement noise, communication latency between the layers and arc extinction in actuator. The paper provides a case study based on the WSCC 9-bus system with overcurrent and under/over-voltage protections on the 230 kV sub-system. The case study illustrates the dynamic behavior of the protective relays modeled by the proposed method and provides the examples for relay reliability tests.**

***Index Terms*—Dynamic simulation, protective relay, cascading failure, power system stability, relay reliability.**

I. INTRODUCTION

A. Motivation

The purpose of protective relays is to isolate a critical component or area as quick as possible and minimize the impact on the overall power system [1]. On the other hand, overconservative relay settings are identified as one of the main causes for cascading failures resulting in large-scale blackouts [2]. Protection system design, therefore, requires a trade-off for speed and selectivity. The increasing penetration of renewable sources and power electronics based devices in modern power system further complicates the requirements for protection systems [3], [4].

In this context, the transient behavior of protection systems needs to be properly understood in order to define optimal protective schemes that enhance the stability and reliability of power system. The dynamic modeling for protective relays that allows the combination of protection system planning and dynamic simulation, therefore, is an evergreen topic. As a matter of fact, an IEEE Task Force sponsored by the IEEE Power System Stability Control subcommittee has been created in 2019 with the purpose of studying the integration of relay models within electromechanical simulations. Under this circumstance, we propose a hybrid dynamic model for protective relays and discuss the impact of overcurrent and over/under-voltage relays on the transient stability analysis of power systems.

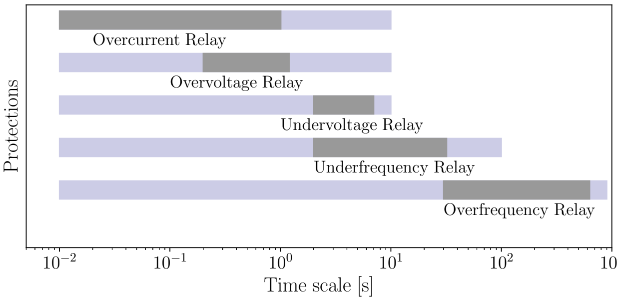

Fig. 1. Timescales of different power system protections. The light gray rectangles indicate the ranges of the possible tripping time of the relays, and the dark gray rectangles indicate the most common ranges.

B. Literature Review

The operation time of a protective relay following a contingency is decided by the severity of the contingency seen by the relay. In general, the more severe the contingency is, the faster the relay will act. The algorithm that computes the time to act according to the infeed signal is abbreviated as *time characteristic* [1]. The time characteristic of a relay indicates the possible tripping time and, in turn, the timescale of the relay. According to the NERC, IEEE and IEC standards [5]–[8].

Figure 1 summarizes the timescales of a variety of common protective relays. From this figure, one can deduce that overcurrent relays usually operate faster than other protections following a fault. Overcurrent relays are thus considered in this paper as the starting point to examine and appreciate the impact of protection systems in transient stability analysis [9].

Several efforts have been made to implement the protective relays in dynamic simulation platforms for power system such as the Dynamic Contingency Analysis Tool (DCAT) developed by Pacific Northwest National Laboratory [10], and Power System Analysis Software Package (PSASP) developed by China Electric Power Research Institute [11]. Auxiliary generic relay models are defined in [12]–[14]. These models effectively emulate the logics of a variety of relays, but are hard to consider their dynamic response when embedded in a power system. The model proposed in this paper overcomes this limitation through a hierarchical structure consisting of measurement, decision-making, and actuator layers. This 3-layer generic model enables easier involvement of specific

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dynamics, e.g., measurement noise, communication latency and arc extinction.

Besides the intrinsic dynamics, unpredictable reliability issues also affect the transient behavior of protection systems and are also the cause for cascading failures. The reliability issues of protective relays include fail operation, abbreviated as *dependability* problem, and miss operation, abbreviated as *security* problem [1]. In previous studies on the combination of protection system planning and dynamic simulation, the concerning of the reliability of protection system is not discussed. This paper fills this gap by addressing the modeling of the reliability issues for a protective relay in dynamic analysis.

C. Contributions

The contributions of the paper are as follows.

- A hierarchical relay model for dynamic simulation, including measurement, decision making and actuator.
- A general modeling approach for the time characteristic of relays.
- A discussion on the modeling of reliability issues of the relays within the proposed hierarchical frame.
- Examples of cascading failures resulting from the actions of protective relays based on a benchmark transmission system.

D. Organization

The remainder of the paper is organized as follows. Section II presents the three-layer relay model for dynamic simulations, a general algorithm to model the time characteristic of the relay and a brief discussion on the modeling of dependability and security issues. In Section III, the WSCC 9-bus system serves to validate the relay model through dynamic simulations and illustrates the cascading failures resulted from the protections. Finally, Section IV draws conclusions and outlines future work directions.

II. GENERIC RELAY MODEL

A. Hierarchical Model

This section introduces a three-layer model for relays in dynamic simulation. The tasks and dynamics for each layer are listed in Table I.

TABLE I
A HIERARCHICAL RELAY MODEL.

Layer	Task	Dynamics
Measurement	Signal collection	Data sampling & processing Measurement noise
Decision Making	Action judgment Trip signal sending	Signal communication Decision-making algorithm
Actuator	Isolating problem	Signal communication Structure-dependable dynamics

The three layers shown in Table I, are "eyes" (measurement), "brain" (decision making) and "muscle" (actuator) of a protective relay. For real-world relays, this three layers can be integrated within one device or separated to different devices distributed far from each other and connected through communication networks [15]. The signal sent from the measurement to the decision-making layer depends on the function of the relay, e.g. the decision-making layer of overcurrent protection is fed by current signal. The signal sent from the decision-making layer to the actuator is the instantaneous tripping signal at the exact time. For layers connected through communication network, time-varying communication delays have to be taken into account [16].

In practice, the structure-dependable dynamics, such as arc extinct, delays the action of an actuator. The magnitude of the delay can be estimated by a precise dynamic model of the actuator. In the remainder of the paper, for simplicity, we consider a constant delay of 0.01 s.

B. Decision-Making Algorithm

As the "brain" of a relay, the decision-making layer decides whether/when to act. The best approach to set up this layer is to model the actual working mechanism of the relay, e.g. the temperature rising equations for a thermal relay, and the build-in algorithm for a micro-processor relay, which, however, may not be practical due to the lack of data from the field to properly set up such a model.

Since the approximate time characteristic for each relay is always accessible, it can be implemented through a simple but effective algorithm shown in Fig. 2. In the flowchart, $x_{\rm pk}$ is the pickup threshold for the relay, τ_r is the time-delay to trip. The tripping signal is sent if and only if $t_r = t_o + \tau_r - t \leq \epsilon$, where ϵ is a small tolerance close to zero. This algorithm is used in the following case study.

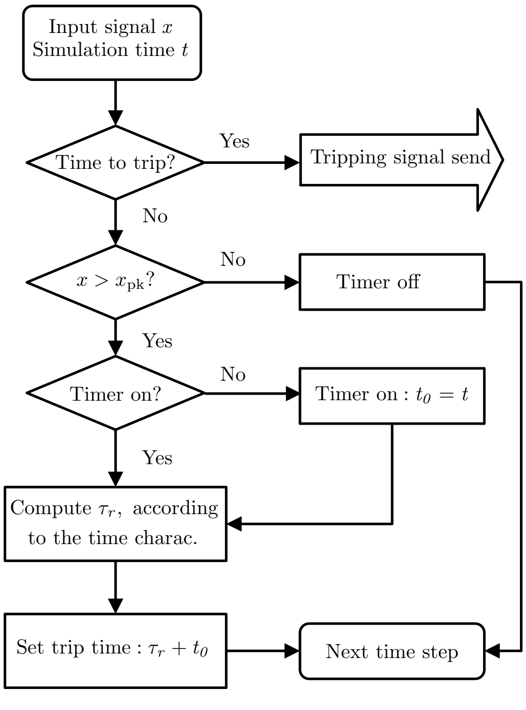

Fig. 2. Decision-making algorithm of a relay.

C. Dependability and Security Issues

In proposed relay model, the dependability issue is represented by a disappearing tripping signal at the decision-making layer or a failure trip of the actuator. The security issues can be modeled as a tripping signal sent at the wrong time or an unexpected operation of the actuator. There a various causes that can originate such issues, as follows.

1) Stochastic signals input to the decision-making layer, caused by the measurement noise or extraneous transients, such as the variants of renewables and loads.
2) Cyber attacks in signal communication processes.
3) Other uncertain issues, occurring randomly according to the estimated possibility, e.g. mechanical switching element failure in the actuator.

III. CASE STUDY

This section aims at validating the proposed generic relay model through overcurrent and under/over-voltage protections, and illustrating the hidden cascading failures caused by the dynamics of protective relays. The case study is based on the WSCC 9-bus system with overcurrent and voltage protections as shown in Fig. 3 and is carried out with the software tool DOME [17]. The steady-state and dynamic parameters of this system can be found in [18].

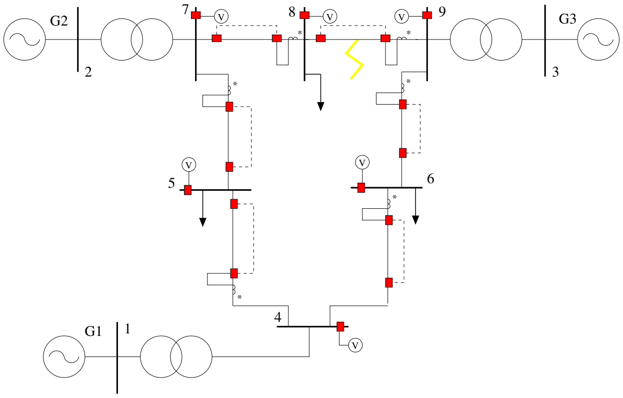

Fig. 3. WSCC 9-bus system with protections.

A. Relay Modeling

This case study considers the current and voltage protections in 230 kV level of the WSCC system with nominal power $S_\mathrm{n} = 100$ MVA. According to IEEE standard [6], the overcurrent protection on transmission line should be directional, which means the relay only sees the current from the set direction. The positive side of the set direction for each overcurrent relay is marked in Fig. 3. For simplicity, the breakers (actuators) installed on the same bus are connected and will act at the same moment. The time characteristic of each overcurrent relay follows the IEC standard [8]:

$$\tau_\mathrm{r} = \mathrm{TMS} \times \frac{\mathrm{A}}{I_\mathrm{r}^\mathrm{B} - 1} \tag{1}$$

where TMS is time multiplier setting, parameters $\mathrm{A}, \mathrm{B} \in \mathbb{R}^+$, and

$$I_\mathrm{r} = \frac{I}{I_\mathrm{pk}} \, . \tag{2}$$

According to [8], the Standard Inverse (SI) setting of time characteristic is $\mathrm{A} = 0.014$, $\mathrm{B} = 0.02$; and Very Inverse (VI) setting is $\mathrm{A} = 13.5$, $\mathrm{B} = 1$. The pickup values for the overcurrent protections are listed in Table II.

TABLE II

I_pk FOR THE OVERCURRENT PROTECTIONS IN THE WSCC 9-BUS SYSTEM.

Line	I_pk [pu]	Line	I_pk [pu]	Line	I_pk [pu]
9-8	0.98	7-8	3.50	9-6	2.62
Line	I_pk [pu]	Line	I_pk [pu]	Line	I_pk [pu]
7-5	3.62	5-4	2.74	6-4	1.78

The time characteristic described by (1) only suits $I_\mathrm{r} \in [1, I_\mathrm{ins})$; for $I_\mathrm{r} \geq I_\mathrm{ins}$, the relay trips instantaneously. In the following tests, all the overcurrent relays use $I_\mathrm{ins} = 25$.

The pickup values and time characteristic for each voltage protection is the same and can be found in Table III. The operation of the voltage protection is to trip the load or the connected transformer on the bus.

TABLE III

TIME CHARACTERISTIC SETTINGS FOR VOLTAGE PROTECTION.

Overvoltage Relay		Undervoltage Relay	
Voltage [pu]	Time [s]	Voltage [pu]	Time [s]
≥ 1.2	0.12	< 0.45	0.15
≥ 1.175	0.25	< 0.65	0.30
≥ 1.15	0.50	< 0.75	1.50
≥ 1.10	2.00	< 0.90	2.50

B. Fault Modeling

In most simulation software tools, a fictitious node has to be placed at the location of a transmission line fault [12], [19]. This method resizes the mathematical model of the power system and, thus, increases the computational burden and may cause numerical issues.

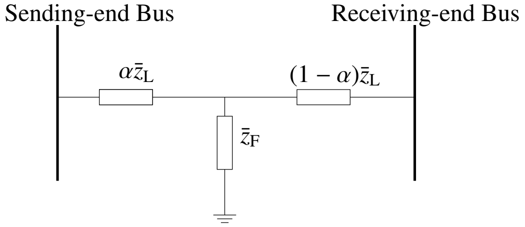

Fig. 4. Parametric model of a three phase fault occurring in a transmission line at a generic location α.

Reference [20] provides an alternative fault modeling approach through the modification of the admittance matrices during the fault. Figure 4 shows the model of a three phase fault occurring in a transmission line, where $\bar{z}_\mathrm{L}$ is the line impedance and $\bar{z}_\mathrm{F}$ is the fault impedance. The location of the fault can be adjusted by tunning the parameter $\alpha \in [0,1]$. The following tests consider the three phase fault occurring in the middle of Line 9-8 ($\alpha = 0.5$) at simulation time $t = 1$ s with $\bar{z}_{\mathrm{F}} = j0.001$ pu(Ω).

C. Dynamic Simulations

Scenario I: Only consider the directional overcurrent relays at 230 kV transmission lines. With $\mathrm{TMS} = 0.1$, the relay at Line 9-8 trips at 0.591 s following the fault with the SI setting, and 0.248 s with the VI setting. Figure 5 shows the trajectories of Bus 9 voltage, I_{r} and τ_{r} of the relay with SI and VI settings.

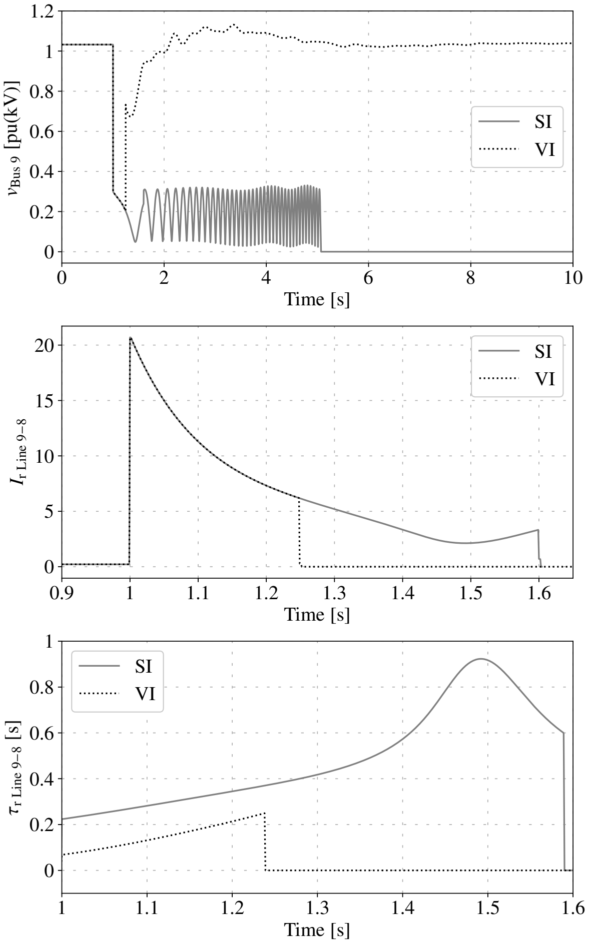

Fig. 5. Trajectories of the transient behavior of WSCC 9-bus system for Scenario I.

According to the trajectory of the voltage at Bus 9 shown in Fig. 5, although both the SI and VI relay trips the fault line, the SI relay acts too slowly to avoid the voltage collapse of the system. Figure 5 indicates that the primary voltage controllers start to response at roughly $t = 1.48$ s resulting in a slight increase in the bus voltage and a corresponding increase in the current through Line 9-8 (indicated by I_{r}) and a decrease in the tripping delay of the relay τ_{r}. This is a typical unstable interaction between protection and controller.

Scenario II: Let us consider both the directional overcurrent relays with VI settings at lines and under/over-voltage relays at buses. In this scenario, the overcurrent relay at Line 9-8 with $\mathrm{TMS} = 0.1$ resulting in a cascading failure following the fault, because the undervoltage relay at Bus 8 and overvoltage relay at Bus 9 acts before the tripping of the fault line.

We have solved a large number of tests with different TMS of the overcurrent relay at Line 9-8. We summarize the actions of protections for three typical scenarios in Table IV and show the results of Bus 8 voltage trajectories in Fig. 6.

TABLE IV
RELAY ACTING TIME FOLLOWING THE FAULT WITH DIFFERENT TMS OF THE OVERCURRENT PROTECTION SCHEME ON LINE 9-8.

Scenario	Overcurrent Relay	Voltage Relays	
TMS	Line 9-8	Bus 8	Bus 9
0.1	-[1]	0.153 s	0.167 s
0.09	0.131 s	0.153 s	-
0.089	0.127 s	-	-

[1]: System collapse after the tripping of the overvoltage relay at Bus 9.

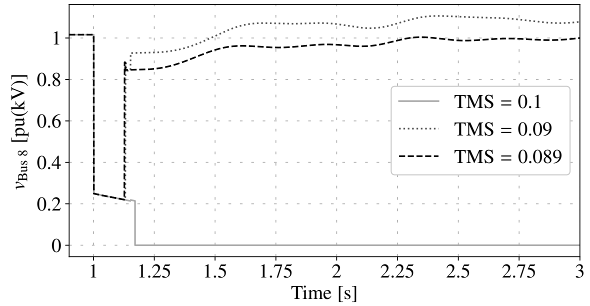

Fig. 6. Trajectories of Bus 8 voltage for Scenario II.

According to Table IV and Fig. 6, the fault has no impact on the normal operation of the power system, if the fault is cleared within 0.127 s, otherwise load shedding on Bus 8 occurs. The system collapses if the fault lasts more than 0.131 s.

D. Relay Reliability Tests

In real-world power systems, there are hierarchical backup protections to avoid the failure of each relay. Since the backup protection is out of the scope of this paper, relay dependability, therefore, is not discussed.

Compared with dependability, the reliability of relays is more difficult to evaluate due to the vast range of scenarios [6]. In this case study, we only consider the reliability issues for the overcurrent relays for pre-fault scenarios. The mis-operation of each overcurrent relay results in the loss of the line, which is similar to a $N-1$ test in traditional dynamic simulations. Taking into account the effect of protections, however, leads to different results. In fact, although the system survives all the $N-1$ contingencies that lead to disconnect a 230 kV transmission line, a cascading phenomenon occurs if Line 7-5 or Line 5-4 trips unexpectedly.

If the overcurrent relay at Line 7-5 mis-operates, the Line 9-8 will trip as well after 0.48 s resulting the off-grid of G2 and thus the system collapses. To illustrate the mechanism of this cascading failure, Fig. 7 shows the trajectories of the current through Line 9-8 for relay security test and $N-1$ test without considering any protection. According to Fig. 7, the dynamic current following the contingency is over 0.98 pu, the pickup threshold of the overcurrent relay at Line 9-8, which causes the action of the relay in the security test. This cascading failure can be avoid through optimizing the settings or changing the set direction of the directional overcurrent relay at Line 9-8.

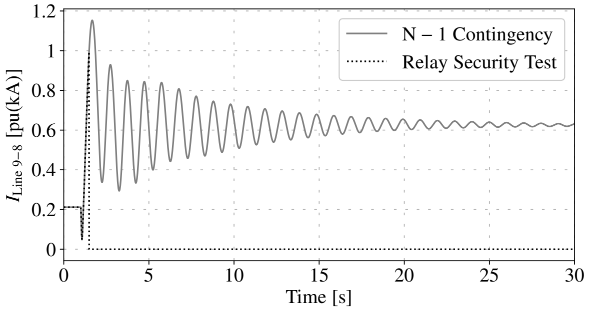

Fig. 7. Trajectories of Line 9-8 current following the trip of Line 7-5.

Following the miss operation of the overcurrent relay at Line 5-4, the undervoltage relay at Bus 5 trips the load after 2.67 s, and the overvoltage relay at Bus 7 trips the transformer after 1.25 s, leading to the disconnection of G2 and the following collapse of the system. This cascading failure can be observed through the trajectories of the voltages at Bus 5 and Bus 7. Figure 8 shows that, after the tripping of the load at Bus 5, both voltages at Buses 5 and 7 hit their limits and trigger the overvoltage relays. This cascading failure can be avoided by adjusting the settings for the voltage protections at Bus 5 and 7, or implementing a selective load shedding scheme at Bus 5 or/and optimal primary voltage controller for synchronous machine G2.

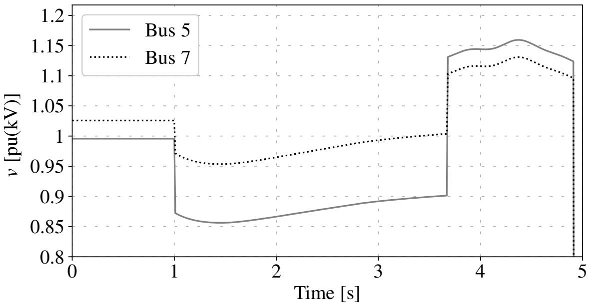

Fig. 8. Trajectories of Bus 5 and 7 voltage following the trip of Line 5-4 with inclusion of voltage protective relays.

IV. CONCLUDING REMARKS AND FUTURE WORK

This paper proposes a relay model consisting of three layers, namely measurement, decision making and actuator for dynamic simulations. This model is validated through the implementation of overcurrent and undervoltage protections in the Python-based dynamic simulation software DOME. The case study based on the WSCC 9-bus system indicates that the modeling of protective relays can assist the optimal planning for the protective schemes to avoid potential cascading failures.

Future work will aim at building a complete library based on the proposed hierarchical model for the commonly used protective relays, including frequency, distance and differential relays. The goal is to carry out a comprehensive study on the cascading failures and of techniques to prevent such a phenomenon.

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