Modelling a Neutral and Phase Overcurrent Directional Relay

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***Abstract*—The aim of this paper is to show how to model a directional overcurrent relay and presents the main issues of such protection in distribution systems with distributed generation (DG). Firstly, the theory about the tools necessary to implement the relay is explained. The operation of the power system and its implementation blocks are addressed. The directional (32), instantaneous and time-delay overcurrent of phase (50 and 51) and neutral (50N and 51N) protection logics are discussed. Next, the relay implementation is inspected in two different case studies: a study to compare, the overcurrent protection actuation in the power system with and without DG and a second study in which the current flow changes the direction in order to test the directional operations.**

I. Introduction

The overcurrent relay is the primary protection in distribution system, as well as backup protection in transmission lines, power transformers, and other equipment. The overcurrent relay operates when the current is above a defined threshold, which depend on the load current and the desired coordination. The relay has to be quick because high currents in the system can damage the equipment and endanger people. In addition, the relay response needs to be reliable to a fault because an improper operation affects power quality indices.

The overcurrent relay has been remained as one of the main protection of distributed power system even with ditributed generation (DG). Therefore, the impact of DG in the power system has been unceasingly investigated [1]–[3] because this new configuration has challenged the coordination.

Researchers have been focused on improving the reliability and efficiency of overcurrent protection in power systems with DG. Several authors have been proposed the use of fault current limiters, whereas others have been suggested the use of adaptive overcurrent protection or optimal coordination of directional overcurrent to solve the impact of DG [4]–[12]. Regarding the overcurrent relay modelling, the research has been concentrated in characteristic curve modelling of the relay [13]–[18], whereas a detailed relay model is not presented.

The knowledge about the relay model is important to identify problems in the protection. The relay modelling is divided in stages, which are: filtering, sampling, phasor estimation, and protection logic. These stages have to be well designed for the relay. For instance, sampling error affects the phasor estimation, consequently, the protection. Therefore, the modelling of relays is useful to identify where the failures are in the improper relay operations.

This work describes a detailed modelling of a directional overcurrent relay, including the theory about current and voltage signal processing and the directional overcurrent protection functions (32,50,51,50N and 51N units) as well. The IEEE bus system with 8 bus was modelled and the modelled overcurrent relay was evaluated under two case studies in order to verify: the DG impact on the overcurrent level and directionality associated to the relay functionality. The results showed that the DG can make the protection slower than a case without DG and the 32 function indicated the fault direction, which can help the coordination solving some DG issues.

This paper is arranged in five sections. Section II presents the digital relay fundamentals and the steps to implement a digital relay. Section III brings five protection functions which compose the directional phase and neutral overcurrent relay. The relay modelling is presented in the section IV, in which each subsection explains the modelling steps. The blocks from the Simulink to compose the system and the relay are named and its main parameters are showed. Section V presents some tests to the modelling relay and the DG impact is presented considering the system with and without DG. The conclusion are given in section VI.

II. Digital Relay Fundamentals

The digital relay is composed of several components such as: anti-aliasing filter, sampler, phasor estimator, and protection logic. Each component has to be well designed in order to provide reliability to the power system. The information about the components helps to understand how the protection works as well as to identify protection failures.

A. Anti-Aliasing Filter

The relay receives the current and voltage signals from the instrument transformers. In the next step, the relay needs to filter these signals to avoid the aliasing effect. One common anti-aliasing filter is the Butterworth module [19]:

$$|H(j\omega)| = \frac{1}{\sqrt{1+\varepsilon^2(\frac{\omega}{\omega_p})^{2n}}}, \quad (1)$$

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where ω is the filter frequency in radians, ω_p is the cut-off frequency in radians, ε is the maximum passband allowed error and n is the filter order.

B. Sampling

The signals from the anti-aliasing filter have to be sampled at least twice the highest frequency contended in the signal, according to the Nyquist-Shannon sampling theorem [20], in order to have a reconstruction without loss of information. Therefore, if the voltage and current frequency signals are 60 Hz, the digital relay will sample these signals from 120 Hz.

The signal sampling is done by the sample-hold followed by the A/D converter. The Sample-Hold holds the signal, while the A/D converts the analogue signal to digital. The most used A/D converters is the Delta-Sigma [21].

C. Phasor Estimation

The phasor estimator uses the sampled signals to estimate the voltage and current phasors at 60 Hz. The ideal phasor estimation needs to be with minimum error, filter all the harmonics and the DC exponential decay with reduced time delay [22]. An example of phasor estimator is the modified cosine filter, which estimates the phasor as follows:

$$Y_{cp} = \frac{2}{N} \sum_{n=1}^{N} y_n \cos(pn\theta), \tag{2}$$

$$Y_{sp} = \frac{Y_{cp-1} - Y_{cp} \cos\theta}{\sin\theta}, \tag{3}$$

where Y_{cp} and Y_{sp} are, respectively, the real and imaginary phasor parts, N is the samples per cycle, θ is the rotation angle, y_n is the sampled signal, and p is the harmonic content. For the fundamental phasor estimation, p must be equal to one.

The modified cosine filter algorithm is simple and it is not affected by the DC exponential decay. However, a fixed frequency to the algorithm has to be assumed. One way to overcome this problem can be an additional algorithm that estimate frequency.

III. Directional Overcurrent Protection

The filtering, sampling and phasor estimation stages are realised before the current and voltage signals being sent to the protection logic. The logic is realised according to the protection functions contained in the relay. This paper cover the phase and neutral overcurrent and the directional functions.

A. Overcurrent Relay

The overcurrent algorithm performs current measurements at the electrical system, which are compared with a defined value. If the system currents exceed the defined value, the algorithm will send a trip signal to open a circuit breaker. The delay of the trip signal depends on the characteristic type such as instantaneous or time-delay overcurrent.

The instantaneous overcurrent function is used when faults cause high currents in the system, which can damage it quickly. Therefore, the relay has to send a trip signal to circuit breaker without delay (instantaneous) [23].

The time-delay overcurrent function operates according to an inverse-time characteristic. When the current is high the operation time is small and when the current is smaller the operation time big. Therefore, this function avoid unnecessary trip due to temporary fault or other events which result in temporary current, sending a quickly trip when the fault causes a high current.

The inverse-time characteristic depends on the selected type of standard which can be already defined such as IEEE, ANSI, IEC or defined by the user. Once set the characteristic, the delay is computed through a specific equation. For instance, the IEC 60255 define the inverse-time characteristic as follow [24]:

$$T = \left(\frac{C}{(\frac{I}{I_s})^{\alpha} - 1} \right) TMS, \tag{4}$$

where T is the relay operation time, C is the constant for relay characteristic, I is the current input, I_s is the defined current, α is the constant representing inverse-time type ($alpha > 0$) and TMS is the time multiplier setting control, which its range is normally between 0.1 to 1.0, depending on the application. Table I summarizes α and C values to define four different types of curves [25], [26].

TABLE I
Types of Inverse Characteristic Curves.

Relay Characteristic	α	C
Standard Inverse	0.02	0.14
Very Inverse	1	13.5
Extremely Inverse	2	80
Long Inverse	1	120

According to ANSI table there are some functions dedicated to overcurrent, such as: instantaneous phase (50), time-delay phase (51), instantaneous neutral (50N), and time-delay neutral overcurrent (51N).

1) Instantaneous Phase Overcurrent Function: The 50 function is enabled when any phase or more than one has the current higher than the pickup value (I_{50}). This function is sensitized:

$$I(k) \geq I_{50}, \tag{5}$$

where $I(k)$ represent the absolute current value at sample k to each phase $(I_A(k), I_B(k), I_C(k))$. The pickup value is calculated as follows:

$$I_{50} = N_{50} I_r, \tag{6}$$

where N_{50} is a constant and Ir is the load current in normal operator state (the reference current).

2) Instantaneous Neutral Overcurrent Function: The 50N function is computed using zero sequence because this sequence measures the unbalance between the phases. The zero sequence current (I_0) is calculated by:

$$I_0(k) = \frac{I_A(k) + I_B(k) + I_C(k)}{3}. \tag{7}$$

When the currents from the system are balanced, the zero sequence current is zero. Therefore, the 50N function is sensitized when the zero sequence current is higher than N_{50N} time the reference current I_r, as follows:

$$I_0(k) \geq N_{50N} I_r, \tag{8}$$

3) Time-Delay Phase Overcurrent Function: The 51 function is sensitized when at least one phase become higher than the pickup value (I_{51}), witch is defined by:

$$I_{51} = N_{51} I_r, \tag{9}$$

where the N_{51} is a constant to define how many times the pickup value is higher than I_r (load current). The N_{51} is usually smaller than N_{50} and higher than one. Therefore, the 51 function is activated when:

$$I(k) \geq I_{51}, \tag{10}$$

The function is activated to start counting according to the defined inverter-time characteristic.

4) Time-Delay Neutral Overcurrent Function: The activation of 51N function occurs when there is unbalance in the system. Therefore, the zero sequence current $I_0(k)$ becomes non-zero and can reach the pickup value (I_{51N}), sensitizing the function to start counting according to the inverse-time characteristic chosen:

$$I_0(k) \geq I_{51N}. \tag{11}$$

The load current I_r in normal operator states the reference to the pickup value, which is defined as N_{51N} times the load current:

$$I_{51N} = N_{51N} I_r, \tag{12}$$

where the constant N_{51N} is usually smaller than N_{50N}. However, those constants can be chosen according to the coordination.

B. Directional Function

When the system is bi-directional, the downstream and upstream overcurrent relays have to be coordinated simultaneous, which makes the coordination complex. In these cases only the overcurrent function cannot provide adequate protection. Therefore, the problem can be solved using the directional function, which gives a radial characteristic to ring system. As consequence the 32 function is just sensitized in one direction.

Two magnitudes are needed to compute the directional function: the polarization magnitude, which is the reference phasor to the relay and the operation magnitude, which is measured from the reference. The polarization and operation magnitudes can be voltage (V_r) and current (I_r) signals, respectively. The directional relay operates when the power flows in a determinate direction. The directionality is defined by phasor comparison between the polarization torque (T_{pol}) and operation (T_{op}). The relay is sensitized when the angle is between $-90°$ to $90°$. The torques are computed by [27]:

$$\begin{aligned} T_{op} &= Z_D \angle\theta I - V, \\ T_{pol} &= Z_D \angle\theta I, \end{aligned} \tag{13}$$

where the impedance $Z_D\angle\theta$ is a relay directional parameter, I is the current phasor and V is reference voltage phasor.

The directional overcurrent function (62) is the directional function with the overcurrent characteristics such as instantaneous, delay-time, or both.

IV. Modelling in Simulink

The Simulink is a dynamic modelling software based on Matlab numerical workspace, designed for simulating dynamic systems. Therefore, the Simulink were chosen to simulate the power system and the relay. In this section, modelling steps are presented followed by the main parameters to each block.

A. Power System

The power systemis based on a IEEE 8 bus system (Fig. 1) composed by a main generator and a distribution generator. This system is simulated in Simulink using the library SimPowerSystem [28], that is dedicated to power system simulations.

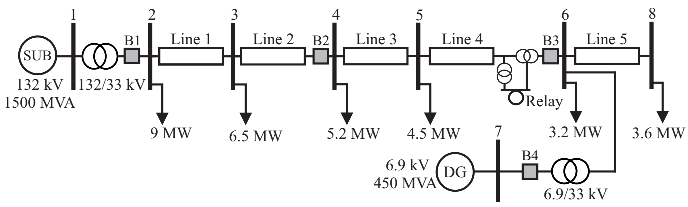

Fig. 1. Power system with DG.

In the power system there are generators, power transformers, current and voltage transformers, relay, breakers, buses, loads and branches. The SymPowerSystem library has some this blocks and the other are implemented by functios in Matlab.

The three-phase source blocks were used to simulate the main generator and the distribution generator, whose the voltage, power and frequency parameters are summarized in Table II.

TABLE II
GENERATOR PARAMETERS.

Generator	Voltage (kV)	Power (MVA)	Frequency(Hz)
Main	132	1500	60
Distributed	6.9	450	60

There is a power transformer connected to each generator, which are simulated by three-phase transformer blocks. In this block, the winding 1 receive the respective voltage from the generators and in the winding 2 receive the feeder voltage (33 kV). The relay inputs are voltage and current vectors and the output is the trip to the breaker.

The breaker is simulated by a three-phase breaker block. In the system there are four breakers, the third is controlled by the relay which is possible chosen the switch time external option in the Simulink block. The other breakers are always closed.

The buses are simulated by a three-phase VI measurement blocks in order to measure the voltage and current in each point along the feeder. The three-phase series RLC load block is used to simulated the loads, which represent the consumers along the feeder.

The branches represent the impedance in each fragment of the feeder, which modelled by three-phase series RLC branch blocks.

B. Filter-Estimator Module

In this module, the inputs are a voltage vector ($V[3]$) and current vector ($I[3]$) from the power system and the outputs are the estimated voltage vector ($V_e[3]$), the estimated current vector ($I_e[3]$) and the ($Sampler$) (Fig. 2). The inputs are filtered by discrete filter blocks which request the numerator and denominator parameters from the filter transference function. The estimators are built using Matlab function blocks. The sampler block is used to control in which moment the estimators have to receive the filtered signals. The outputs are send to the protection logic module.

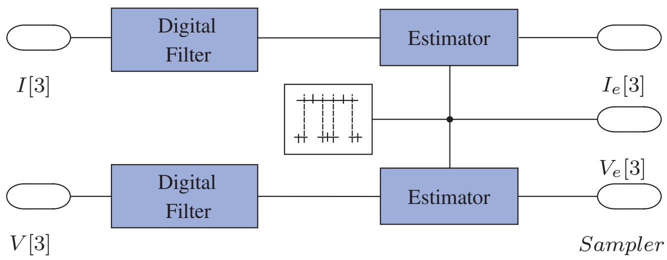

Fig. 2. Filter-estimator module.

C. Protection Logic Module

The protection logic module covers the three protection logic: directional, phase and neutral overcurrent logics (Fig. 3). Each one is implemented using Matlab function blocks and separated in different subsystems. The phase and neutral overcurrent logics use just the estimated current. However, the directional logic uses the estimated voltage and current to identify the power direction. An activator using the relational operator block is used to limit when the directional function has to begin actuated because the power flow sensitize the function in steady state.

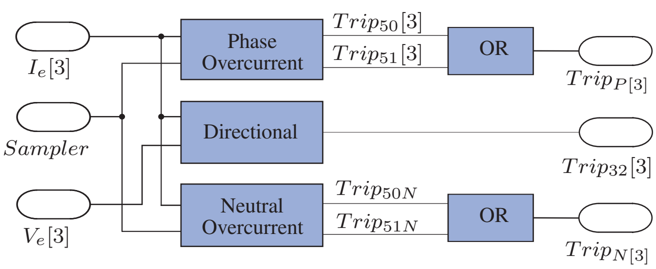

Fig. 3. Protection logic module.

The input parameters come from the filter-estimator module, which are estimated voltage and current vectors ($V_e[3]$ and $I_e[3]$). The $Trip_{32}[3]$ is the output vector from Directional block. The outputs of Phase Overcurrent block are the $Trip_{50}[3]$ (instantaneous phase overcurrent) and $Trip_{51}[3]$ (delay-time phase overcurrent) which is selected by a OR operator and the $Trip_P[3]$ is the output relative to phase units. The same occurs with the Overcurrent Neutral block which the $Trip_{50N}$ (instantaneous overcurrent neutral) and $Trip_{51N}$ (delay-time neutral overcurrent) are also selected by OR operator and the $Trip_N$ is the output relative to neutral units.

D. Trips Logic Module

In order to implement the neutral and phase overcurrent directional relay, logic operator blocks AND and OR are used. The directional unit is a condition to the other units operate. The inputs $Trip_{32}[3]$ and $Trip_{P[3]}$ are vectors with three elements and the $Trip_N$ has just one element, for this reason a demultiplexer from Matlab is used to transform the $Trip_{32}[3]$ in three separated output which becomes the inputs of the OR operator. The output of OR operator can be used to do the logic with $Trip_N$ (Fig. 4).

Therefore, the neutral and phase overcurrent units have to realize the AND operation with the directional unit. The results of the AND operation to each overcurrent unit are sent to the OR operator, which is activated if at least one of the AND operator is true. The trip is sent to a Matlab function where has a logic to emulate the mechanical delay of the circuit breaker. The trips logic subsystem output is $Trip$, which is the command to open or not the breaker in the power system.

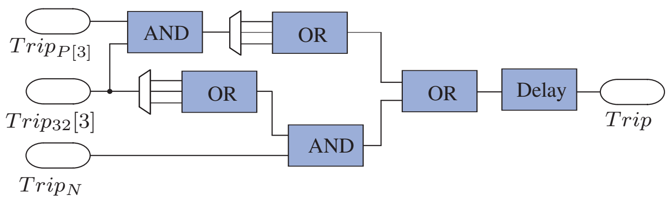

Fig. 4. Trips logic module.

V. Case Studies

In order to evaluate the performance of the implemented relay, as well as the impact of the DG in the overcurrent protection, two case studies were simulated. The first one analyses the DG impact in the fault overcurrent level and the second one presents the directional function assessment.

The overcurrent functions were based on the IEC standards for very inverse curves and the TMS constant was considered 0.2. A single line-to-grounded (SLG) fault was applied in 0.2 s with fault resistance $r_F = 15\Omega$ for all simulations. The considered breaker delay was considered 3 cycles and the directional function was sensitized to upstream faults. The sampler time of simulation was $\frac{1}{15360}$ s.

A. Impact of the DG in the Overcurrent Protection

The DG modifies the power flow to both sides and changes the level of the fault overcurrent, which impacts the relay coordination. Therefore, a fault is simulated in a power system with and without the DG in order to investigate the overcurrent protection behaviour and possible solutions.

The system in Fig. 1 was simulated with and without DG considering a single line-to-ground (SLG) fault on bus 8. The phase and neutral currents were measured by the relay B3 before bus 6 as well as the Fourier absolute current and the relay flags are depicted in Figs. 5 and 6.

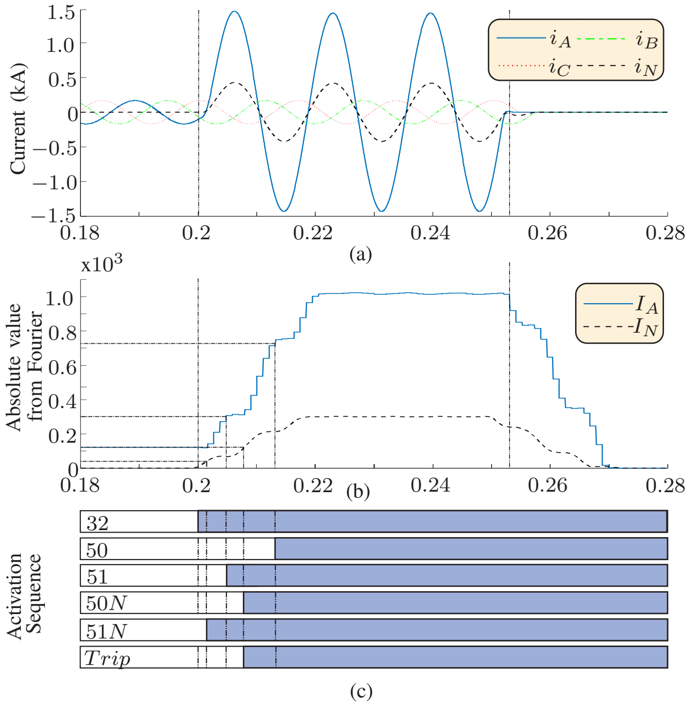

Fig. 5. Upstream fault without DG: a) currents i_A, i_B, i_C and i_N; b) absolute currents I_A and I_N; c) relay activation flags.

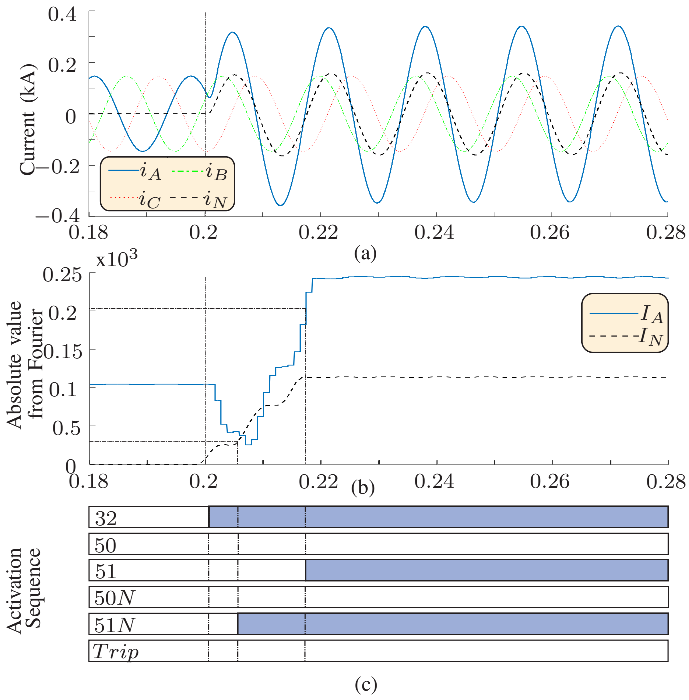

Fig. 6. Upstream fault with DG: a) currents i_A, i_B, i_C and i_N; b) absolute currents I_A and I_N; c) relay activation flags.

Without DG (Fig. 5), the faulted phase and neutral currents increased and sensitized the overcurrent units 50, 50N, 51, 51N as well as the directional function because the fault is upstream the relay. Since the instantaneous units 50 and 50N were sensitized, a fast trip was generated in few miliseconds. The fault was cleared few cycles after the trip due to the mechanical delay associated to the circuit breaker.

With DG (Fig. 6), the phase A and neutral currents increased during the fault as expected. However, the current levels were lower than the previous simulation, because the breaker B3 was before the DG which also supplies current to fault and just the time-delay units 51 and 51N with the direction function were sensitized. Therefore, the 51 and 51N units started the counting and the relay delayed the trip signal to the breaker in about 30 cycles according to the overcurrent level and the selected inverse characteristic curve.

Besides the directional function, the parametrization of the overcurrent functions, which is out of the scope of this paper, must be set properly in distribution system with DG in order to overcome the loss of sensibility.

B. Directional Function Assessment

The directional unit actuates only in one direction, which gives directionality capabilities to the overcurrent units as requested by the overcurrent protection in distribution system with DG, since with DG a fault can impose power flow in both directions.

Fig. 7 depicts the phase and neutral currents measured by the relay B3 to a SLG fault at bus 3 as well as the Fourier absolute values of the faulted currents and the relay flags related to a downstream SLG fault on bus 4.

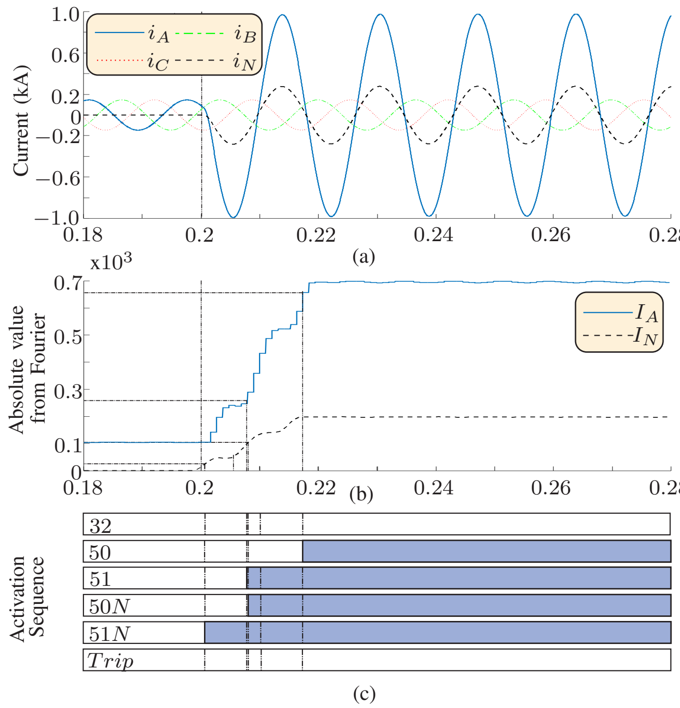

Fig. 7. Downstream fault: a) currents i_A, i_B, i_C and i_N; b) absolute currents I_A and I_N; c) relay activation flags.

According to Fig. 7, the downstream fault imposed overcurrent in the faulted currents sensitizing the overcurrents functions. However, the directional function blocked the trip since the relay was set to trip only for upstream fault.

VI. Conclusion

The theoretical concepts about the overcurrent digital relay as well as its detailed implementation were presented in this paper. The steps to implement the overcurrent relay were discussed. The overcurrent and directional equations were implemented and evaluated using case studies in a distribution power system with and without DG.

The current during upstream faults to the overcurrent relay in power systems with DG presented less expressive increase than the current in power systems without DG, which make the protection less sensitive. Therefore, the overcurrent functions tend to delay the trip, exposing equipment and people to danger. In addition, the directional function were essential to block the trip in downstream fault when the relay was set to act just in upstream faults.

The modelling of a relay is possible following specific steps. Once modelled, the relay can be implemented in any program that support the power system simulation for assessment. In addition, the knowledge about the relay modelling and its performance under specific situations help to design relays for supplying the protection system needs.

References

[1] C. Mozina, "Impact of green power distributed generation," *IEEE Industry Applications Magazine*, 2010.

[2] P. P. Barker and R. W. De Mello, "Determining the impact of distributed generation on power systems. i. radial distribution systems," in *Power Engineering Society Summer Meeting, 2000. IEEE*, vol. 3, pp. 1645–1656, IEEE, 2000.

[3] H. L. Willis, *Distributed power generation: planning and evaluation*. CRC Press, 2000.

[4] G. Tang and M. Iravani, "Application of a fault current limiter to minimize distributed generation impact on coordinated relay protection," in *Int. Conf. Power Systems Transients, Montreal, QC, Canada*, pp. 19–23, 2005.

[5] A. Agheli, H. A. Abyaneh, R. M. Chabanloo, and H. H. Dezaki, "Reducing the impact of dg in distribution networks protection using fault current limiters," in *Power Engineering and Optimization Conference (PEOCO), 2010 4th International*, pp. 298–303, IEEE, 2010.

[6] W. El-Khattam and T. S. Sidhu, "Resolving the impact of distributed renewable generation on directional overcurrent relay coordination: a case study," *IET Renewable power generation*, vol. 3, no. 4, pp. 415–425, 2009.

[7] M. Baran and I. El-Markabi, "Adaptive over current protection for distribution feeders with distributed generators," in *Power Systems Conference and Exposition, 2004. IEEE PES*, pp. 715–719, IEEE, 2004.

[8] N. Schäfer, T. Degner, A. Shustov, T. Keil, and J. Jäger, "Adaptive protection system for distribution networks with distributed energy resources," 2010.

[9] M. Ojaghi, Z. Sudi, and J. Faiz, "Implementation of full adaptive technique to optimal coordination of overcurrent relays," *Power Delivery, IEEE Transactions on*, vol. 28, no. 1, pp. 235–244, 2013.

[10] M. Ezzeddine, R. Kaczmarek, and M. Iftikhar, "Coordination of directional overcurrent relays using a novel method to select their settings," *Generation, Transmission & Distribution, IET*, vol. 5, no. 7, pp. 743–750, 2011.

[11] R. Chabanloo, H. A. Abyaneh, A. Agheli, and H. Rastegar, "Overcurrent relays coordination considering transient behaviour of fault current limiter and distributed generation in distribution power network," *IET generation, transmission & distribution*, vol. 5, no. 9, pp. 903–911, 2011.

[12] S. M. Brahma, A. Girgis, *et al.*, "Development of adaptive protection scheme for distribution systems with high penetration of distributed generation," *IEEE Trans. Power Del.*, vol. 19, no. 1, pp. 56–63, 2004.

[13] M. Meshkin, K. Faez, H. Abyaneh, and H. Kanan, "Application of cascade correlation neural network in modelling of overcurrent relay characteristics," in *GCC Conference (GCC), 2006 IEEE*, pp. 1–6, March 2006.

[14] A. Tjahjono, A. Priyadi, M. Purnomo, and M. Pujiantara, "Overcurrent relay curve modeling using adaptive neuro fuzzy inference system," in *Electrical Engineering and Informatics (MICEEI), 2014 Makassar International Conference on*, pp. 103–108, Nov 2014.

[15] H. B. Funmilayo, J. Silva, K. L. Butler-Purry, *et al.*, "Overcurrent protection for the ieee 34-node radial test feeder," *Power Delivery, IEEE Transactions on*, vol. 27, no. 2, pp. 459–468, 2012.

[16] D. Negrao, J. Vieira, and S. de Souza, "Methodology for modeling overcurrent relays with non-standard curves by using logarithmic-linear correction," in *PES General Meeting — Conference Exposition, 2014 IEEE*, pp. 1–5, July 2014.

[17] T. Bajanek, "Overcurrent protection relay model using iec 61850-9-2 sampled values," in *Electric Power Engineering (EPE), Proccedings of the 2014 15th International Scientific Conference on*, pp. 101–106, May 2014.

[18] Y. L. Goh, A. Ramasamy, A. Abidin, and F. Nagi, "Modelling of overcurrent relay using digital signal processor," in *Industrial Electronics Applications (ISIEA), 2010 IEEE Symposium on*, pp. 367–370, Oct 2010.

[19] A. S. Sedra and K. C. Smith, *Microelectronic circuits*, vol. 1. New York: Oxford University Press, 2004.

[20] A. V. Oppenheim, R. W. Schafer, J. R. Buck, *et al.*, *Discrete-time signal processing*, vol. 2. Prentice-hall Englewood Cliffs, 1989.

[21] A. Phadke and J. Thorp, *Computer Relaying for Power Systems*. Wiley, 2009.

[22] E. O. Schweitzer and D. Hou, "Filtering for protective relays," in *WESCANEX 93.'Communications, Computers and Power in the Modern Environment.'Conference Proceedings., IEEE*, pp. 15–23, IEEE, 1993.

[23] F. Costa, A. Monti, and S. Paiva, "Overcurrent protection in distribution systems with distributed generation based on the real-time boundary wavelet transform," *Power Delivery, IEEE Transactions on*, vol. PP, no. 99, pp. 1–1, 2015.

[24] G. Benmouyal, M. Meisinger, J. Burnworth, W. Elmore, K. Freirich, P. Kotos, P. Leblanc, P. Lerley, J. McConnell, J. Mizener, J. Pinto de Sa, R. Ramaswami, M. Sachdev, W. Strang, J. Waldron, S. Watansiriroch, and S. Zocholl, "Ieee standard inverse-time characteristic equations for overcurrent relays," *Power Delivery, IEEE Transactions on*, vol. 14, pp. 868–872, Jul 1999.

[25] J. Tan, P. McLaren, R. Jayasinghe, and P. Wilson, "Software model for inverse time overcurrent relays incorporating iec and ieee standard curves," in *Electrical and Computer Engineering, 2002. IEEE CCECE 2002. Canadian Conference on*, vol. 1, pp. 37–41 vol.1, 2002.

[26] H. Darwish, A. Taalab, and H. Assal, "A novel overcurrent relay with universal characteristics," in *Transmission and Distribution Conference and Exposition, 2001 IEEE/PES*, vol. 1, pp. 53–58 vol.1, 2001.

[27] B. Kasztenny and D. Finney, "Fundamentals of distance protection," in *Protective Relay Engineers, 2008 61st Annual Conference for*, pp. 1 –34, april 2008.

[28] Hydro-Qubec, *SimPowerSystem*^{TM}*, User's Guide (Second Generation)*. MathWorks disponvel em: http://www.mathworks.com, 2013.