MODELING OF PROTECTION RELAYS AND RENEWABLE ENERGY SOURCES FOR MICROGRID SYSTEMS

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ABSTRACT

Further research and development in the field of microgrids and related modelling and testing will be necessary for successful application in practice, which will require various model elements. It will be possible to create near-real test microgrids to help better understand the behaviour of such grids. For this reason, it is necessary to develop elements of independent parts that appear in distribution networks that will experience conversion to microgrids in the future. Therefore, this article will describe and propose models of basic protection relays, whose potential for application in microgrids is high. The article will additionally provide models of some power supplies that will be found in such reconstructed new grids.

Keywords: *protection relay, power source, renewable energy sources, microgrid, simulation program Matlab&Simulink.*

1. INTRODUCTION

In addition to the increasing demand for electricity, distribution companies are constantly trying to increase network reliability. One of the certain effects on consumption is the modern equipment that manufacturers are trying to produce for the highest possible energy efficiency class. This means the replacement of old appliances with excessive consumption limits this constant consumption growth. Due to the active involvement of participants, the native centralised system is being transformed into a decentralised system, involving consumers in system management. This penetration of renewable electricity sources into the distribution network results in changes. These changes bring the fulfilment of preconditions for the application of smart grids and microgrids.

The building or transforming of the current system into a smart grid will require a great deal of effort for a successful application that will lead to increased reliability, reduced losses, the use of renewable energy sources, and the active involvement of customers in the management process. The chief problem with microgrids is the design of suitable power supplies to suit island operations in all conditions. This is also the primary advantage of the microgrid over the current system, which ensures uninterrupted power to consumers and a significant increase in reliability [1] – [3].

However, the design of the protection system is complicated by this, as not all problems related to the management of such networks are solved. When designing a new protection system, the lowest possible time delay will be considered for the protection to respond to a fault [2], [4]. For this reason, this article deals with the design of programmable protection relays for the simulation programme MATLAB & Simulink and is a continuation of the article Design of energy source models for a microgrid system from the Scientific Conference of Young Researchers [2].

The problem of modelling differential protection has been discussed in detail in [5], and the paper describes a model built from the basic parts of the Simulink library. A more general overview of the design and communication of protection relays is provided in [6]. The problem of directional protection is analysed in [7], which presents the problem in detail. The problem of a mathematical model of a substation for industrial enterprise and testing is discussed by [8] and [9], which review the development of the models. The modelling of overcurrent protective relays is discussed in [10], which highlights the favoured graphical forking of the MATLAB and Simulink environments. For this reason, for accelerated research in the field of protection systems, it is faster to test new methods first in a simulation environment and only after achieving sufficient results to apply testing in practice.

2. MICROGRID

A key feature of the microgrid system is the seamless transition from island operation to grid operation while leveraging the island mode auto-control capability. In the event of a fault, local microgrid systems can increase system reliability by switching to islanded mode as local resources and renewable energy sources (RES) continue to power the microgrid system. The benefits of microgrids will eventually eliminate the technical challenges of controlling and protecting microgrid systems. A significant challenge in microgrid systems is the design of an appropriate energy mix of local energy sources, RES and proper design can help solve the control and system protection problems of the power system [11].

The problems with applying these structures in practise are several, but the essential problems are with a suitable mix of energy sources for such systems and with the transmission infrastructure itself, which is undesigned for such changes. The key will be to determine the size of the area that such a microgrid system will control [2].

3. MODELING RENEWABLE ENERGY SOURCES

The following section provides a proposal and evaluation of the protection system for promising renewable sources in Slovakia. The next models use the Simscape Power System library (v7.5, MathWork, CA, USA) in Simulink (v9.10.0.1851785, MathWork, CA, USA). For the following RES models, we will consider photovoltaic stations, battery storage tanks, thermal power plants, and hydroelectric power plants, which would be the most suitable for Slovakia [2]. This article will mainly propose solutions for the parameterization of overcurrent protection relays, the setting of which is much more complicated for their application in microgrids than in the current distribution network.

3.1. Model of solar array and battery storage system

The territory of the Slovak Republic offers a promising use of solar energy, mainly for the southern areas, where there is the greatest perspective for their application, while the highest output per m^2 can be obtained from Komárno to Nitra. The model of the photovoltaic (PV) array was designed for an output of 100 kW. This wattage has been designed as a reference and can be easily changed by the value of the scale array multiplier for 100 kW. The PV array has seven modules per string connected in series, which are connected into thirty-five strings in parallel. The PV station model has two inputs: the first for irradiation with a basic setup of 1000 W/m^2 and the second for temperature with a basic setup of 30 °C. The model can be customised as shown in Fig. 2. The battery storage system uses lithium-ion batteries with an output voltage of 515 V, a wattage of 100 kW, and a capacity of 250 Ah. The battery storage model does not contain any inputs, unlike the PV station.

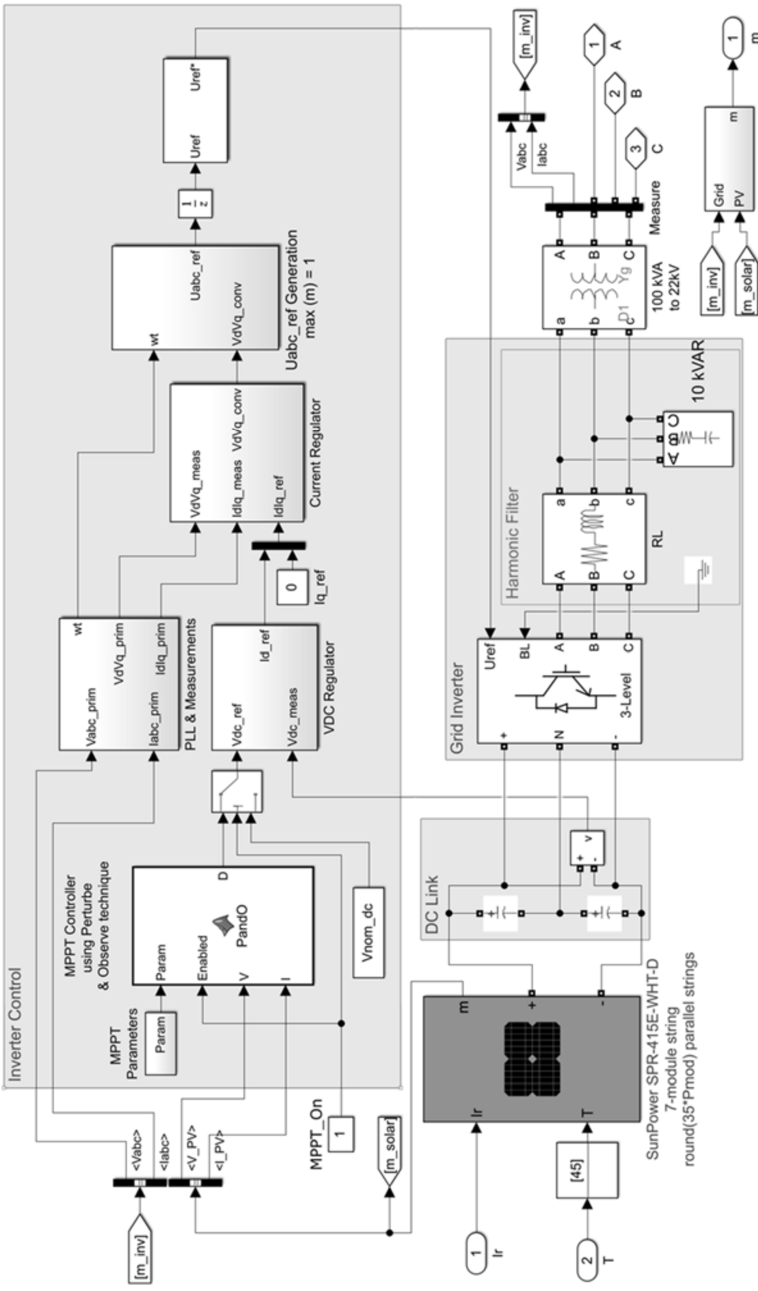


Fig. 1 Schematic model of the solar array [1]

Both models have galvanic separation from the distribution network via a transformer and are additionally filtered for the effect of higher harmonics. The PV output measurement output contains the following parameters: output voltage, output current, active and reactive power values, DC voltage and current entering the inverter, irradiation, and temperature. The measurement output of the battery storage system contains the following parameters: output voltage, output current, values of active and reactive power, an equivalent number of cycles, maximum capacity, state of charge, DC voltage, and current entering the inverter. Structurally, the models use the same elements as shown in Fig. 1 and Fig.3 [2].

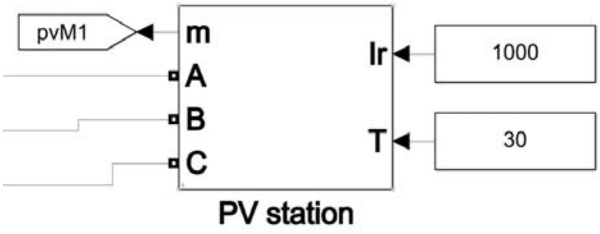


Fig. 2 Model of photovoltaic station

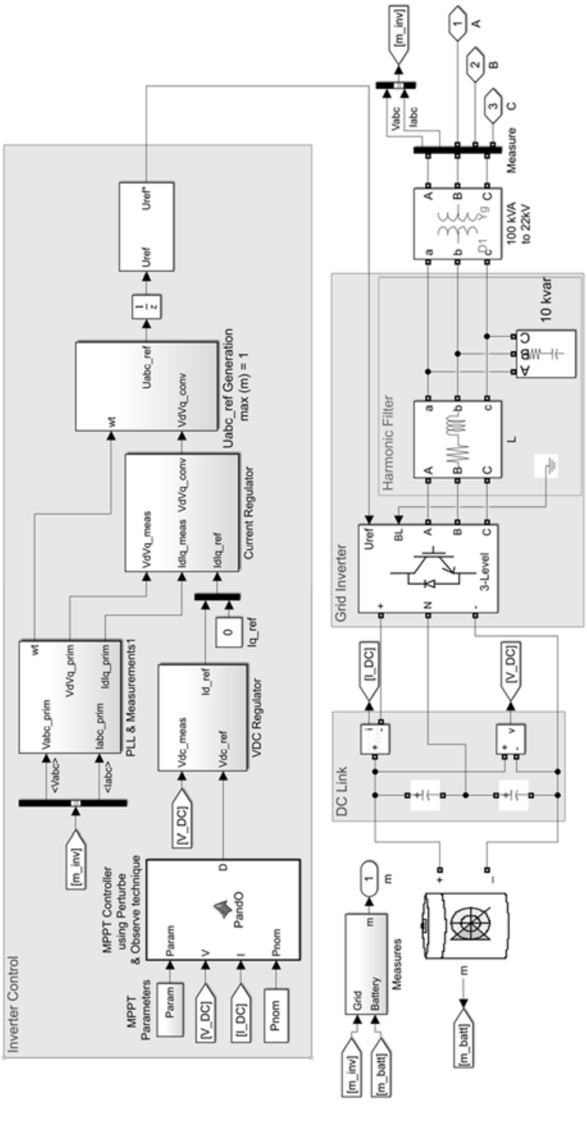


Fig. 3 Schematic model of battery storage system [1]

To secure such renewable resources, we can currently use directional overcurrent protection, which we can possibly improve with differential protection. As shown in Fig. 4, we can currently use various protection relays, while the use of only purely time-overcurrent relays for protection is not completely suitable due to the problematic setting. The dynamic behaviour of weather-dependent renewables, like solar systems, complicates this even more.

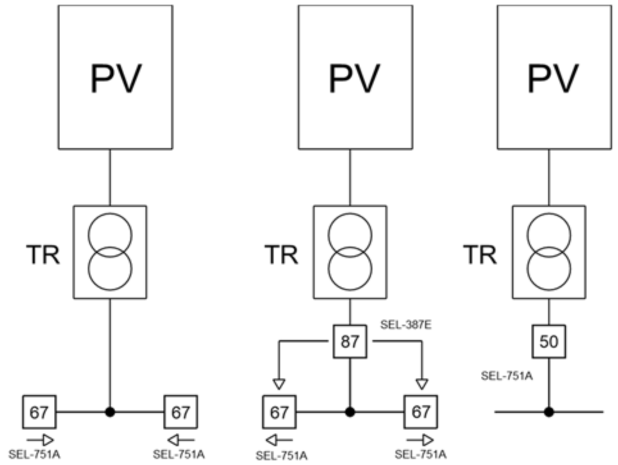


Fig. 4 Solar array protection options [12]

3.2. Model of Hydropower Plant

Thanks to the extensive water system in the Slovak Republic, we offer great potential for the use of water energy for electricity production. Currently, Slovakia has 105 hydroelectric power plants, and their output is quite diverse, with a total power output of 2567 MW. Čierny Váh is without a doubt one of the most widely used hydroelectric power plants. It is a pumped-up storage hydroelectric power plant that plays a key role in regulating the electricity system.

The design of the hydroelectric plant model was considerably more classic than the design of the solar array or battery system, as shown in Fig. 5. It also follows from the number of modules used and, subsequently, from their settings. The hydroelectric power plant model was designed for 125 kW [2]. The hydropower plant contains a synchronous generator, a hydraulic turbine and governor, and an excitation system that represents the dynamics of the hydropower plant. The hydro power plant model has three inputs, the first for the desired reference speed (in pu) with a basic set of 1, the second for the desired reference voltage with a basic set of 1, and the third for the power variation option (in pu) with a basic setting of 0.75 as shown in **Fig. 11**. The model has been designed directly for 22 kV distribution voltage, so it can be directly connected to the distribution network and the model has its own consumption (shunt). The measurement output of the hydropower plant contains the following parameters: output voltage, output current, active and reactive power values (also in pu), and rotor speed. The protection of hydropower plants is ensured by at least the following protections: time overcurrent, stator overload, overvoltage, and reverse power. Compared to a solar field protection system or battery storage system, the protection problem is easier, even if the setup looks more complicated. For larger generator outputs of 1 MVA and above, differential protection is already used for protection, as shown in Fig. 6.

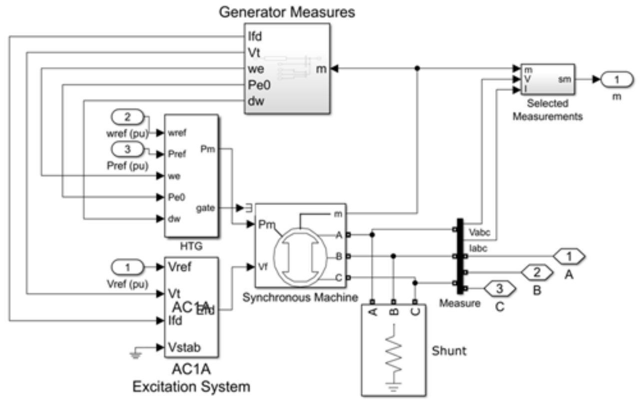


Fig. 5 Schematic model of hydropower plant [1]

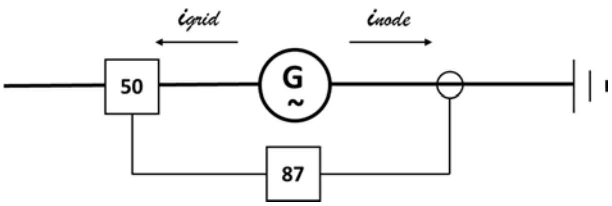


Fig. 6 Protection system of hydropower plant

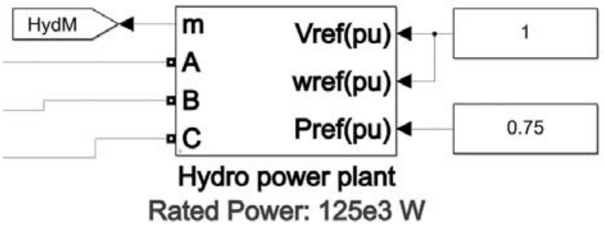


Fig. 7 Model of hydropower plant

3.3. Model of Thermal Power Plant

The future of thermal power plants is considerably complicated in the whole of Europe as well as in the territory of the Slovak Republic. Coal-fired thermal power plants are unsustainable due to their inability to meet increasingly stringent emission requirements. When considering the issue of supply and storage, these types of power plants are currently at the end of their service life. However, thermal power plants can use gas, either natural or bio, or biomass as fuel. The issue with this type of resource is the cultivation of the fuel, where a large area is needed for sufficient production.

The design of the thermal power plant model was as classic as the design of the hydro power plant, as shown in **Fig. 8**. This also results from the number of modules used and, consequently, in their settings. The thermal power plant model was designed for an output of 105 kW [2]. The thermal power plant contains a synchronous generator, a steam turbine, a governor, and an excitation system, which represents the dynamics of the thermal power plant. The thermal power plant model has three inputs: the first for the required reference speed (in pu) with basic setting 1, the second for the required reference voltage with basic setting 1, and the third for the possibility of power change (in pu) with basic setting 0.75 as shown in Fig. 9. The model is designed directly for a distribution voltage of 22 kV, so it can be directly connected to the distribution network and the model has its own consumption (Shunt). The measuring output of a thermal power plant contains the following parameters: output voltage, output current, values of active and reactive power (also in pu), and rotor speed.

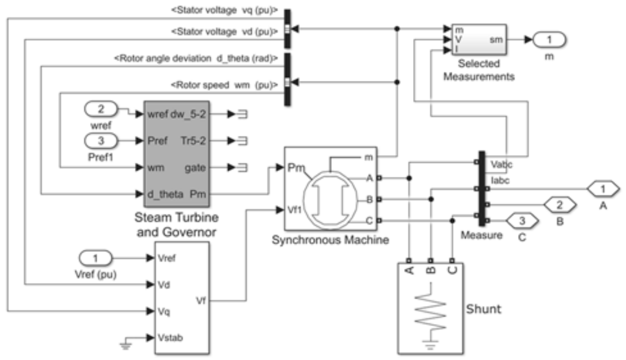


Fig. 8 Schematic model of thermal power plant [1]

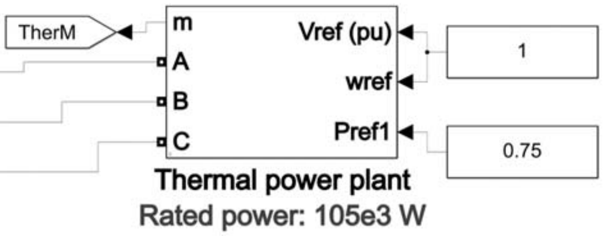


Fig. 9 Model of thermal power plant

Protecting thermal power plants is a bit more complicated than hydropower, as it is a system that uses much higher speeds and results in the inertia of the power plant itself, which cannot be shut down as quickly as, for example, a hydropower plant. The following protections are sufficient to secure compact sources up to 1 MVA: time-overcurrent relay, stator overload, and overvoltage. To secure sources more massive than 1 MVA, protection is required with at least the following protections: time overcurrent, stator overload, differential, overvoltage, stator ground, rotor ground, and reverse power.

4. MODELING PROTECTION SYSTEM

4.1. Model of overcurrent protection

The model was designed using the basic parts from the available libraries for Simulink. The protection relay model works on a simple principle where it uses the input data to evaluate whether it is a permissive state or a fault state, as also shown in **Fig. 10**. The protection input data is the measurement current, the voltage input for detecting the direction of current flow, and the simulation time used to calculate the tripping delay. The measurement is true RMS. To verify that this is a fault condition, the protection reacts with a 10 ms delay, during which it keeps checking the measured values. The model has a selective action function where if the protection relay detects a fault state and the measured value falls below the setup value until response, the protection relay resets the fault state. The model considers the ideal current transformer and potential transformer.

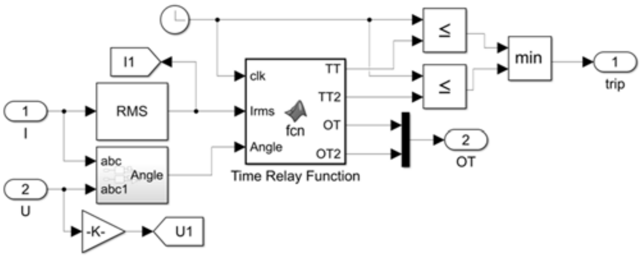


Fig. 10 Schematic model of overcurrent programmable protection relay

The overcurrent programmable protection model was created to meet the requirements for accuracy and set of currently used protections. Such reprogramming will be the most cost-effective choice. The model receives a current and voltage input for the use of a directional power relay. Furthermore, the model has two outputs for the power circuit breaker (TRIP) and the operating time (OT) to display the exact time of operation.

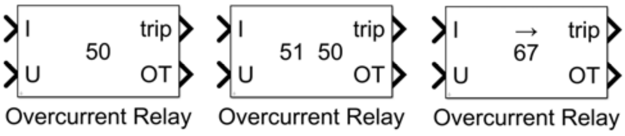


Fig. 11 Model of overcurrent programmable protection relay

The model has a display of the set function according to the ANSI code. As shown in **Fig. 11,** when setting only one function, such as the 50–definite time function or the 67–direction function, the set function with the current protection will appear on the model. When setting multiple functions, multiple codes will be displayed on the model according to the set functions, in this case, 51 and 50. The model also contains several types of tripping characteristics for setting the time-dependent function. The calculation of the tripping characteristic for time-dependent inverse overcurrent protection is according to equation (1).

$$t(s) = \frac{A \times Td + K1}{M^P - Q} + B \times Td + K2 \tag{1}$$

Where:

t(s) represents the theoretical tripping time (s),

A is curve type constant with a default range of (0.14 to 120),

Td is the time index scaling the time axis of the curve (Time setting for the element),

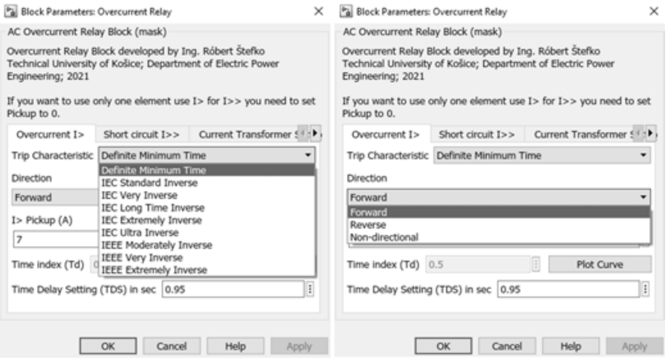
M is the ratio of I/Ipick-up where I is the actual current, and $I_{\text{pick-up}}$ represents the pick-up current setting,

P is a curved type of constant with a default in the range (0.02 to 2),

Q is a curved type of constant by default (1),

K1, **K2,** and **B** are curved type constant with a value of 0 by default.

Parameters to be set by the user for fine-tuning the characteristic are A, B, P, Q, K1, and K2. As shown in Fig. 12 up to eight different time-dependent functions and one definite time function can be selected in the model. The model also has a choice using the directional function option.


Block Parameters: Overcurrent Relay

AC Overcurrent Relay Block (mask)

Overcurrent Relay Block developed by Ing. Róbert Štefko
Technical University of Košice; Department of Electric Power
Engineering; 2021

If you want to use only one element use I> for I>> you need to set Pickup to 0.

Trip Characteristic: Definite Minimum Time

- Definite Minimum Time
- IEC Standard Inverse
- IEC Very Inverse
- IEC Long Time Inverse
- IEC Extremely Inverse
- IEC Ultra Inverse
- IEEE Moderately Inverse
- IEEE Very Inverse
- IEEE Extremely Inverse

Direction: Forward

I> Pickup (A): 7

Time Delay Setting (TDS) in sec: 0.95

Block Parameters: Overcurrent Relay

AC Overcurrent Relay Block (mask)

Overcurrent Relay Block developed by Ing. Róbert Štefko
Technical University of Košice; Department of Electric Power
Engineering; 2021

If you want to use only one element use I> for I>> you need to set Pickup to 0.

Trip Characteristic: Definite Minimum Time

Direction: Forward

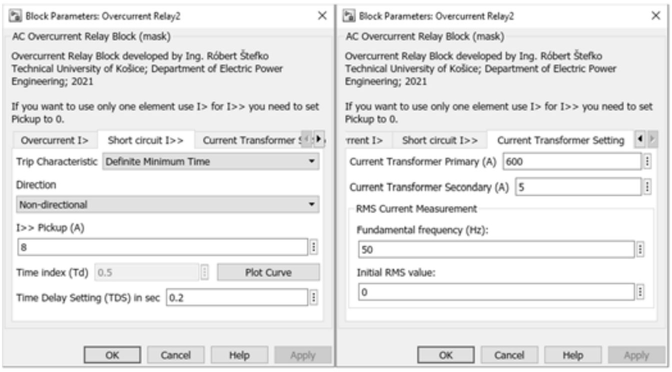
- Forward
- Reverse
- Non-directional

Time index (Td): 0.5

Time Delay Setting (TDS) in sec: 0.95

Fig. 12 List of tripping characteristics for overcurrent time protection and select from options for directional protection

The same setting as for overload can be set for the second stage for short circuits as shown in Fig. 13. The last option for setting the protection relay is to set the parameters of the instrument current transformer (CT) and main frequency.


Block Parameters: Overcurrent Relay2

AC Overcurrent Relay Block (mask)

Overcurrent Relay Block developed by Ing. Róbert Štefko
Technical University of Košice; Department of Electric Power
Engineering; 2021

If you want to use only one element use I> for I>> you need to set Pickup to 0.

Trip Characteristic: Definite Minimum Time

Direction: Non-directional

I>> Pickup (A): 8

Time index (Td): 0.5

Time Delay Setting (TDS) in sec: 0.2

Block Parameters: Overcurrent Relay2

AC Overcurrent Relay Block (mask)

Overcurrent Relay Block developed by Ing. Róbert Štefko
Technical University of Košice; Department of Electric Power
Engineering; 2021

If you want to use only one element use I> for I>> you need to set Pickup to 0.

Current Transformer Primary (A): 600

Current Transformer Secondary (A): 5

RMS Current Measurement

Fundamental frequency (Hz): 50

Initial RMS value: 0

Fig. 13 Overcurrent protection setting options for grade types and CT parameter settings

The overcurrent relay model was tested on the simple example shown in Fig. 14, which consists of a power supply, one transformer (TR), load (Load5), a power line, and two circuit breakers.

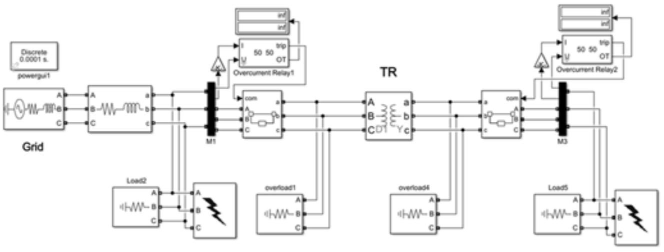


Fig. 14 Test setup of overcurrent protection models

The first testing of overcurrent relays will consist of testing the first stage for overload. In the first model situation, to test the functionality of the models, we only consider the connection of Load5. The result of the test is that the protections did not react due to a lower measured current than was set on the individual protective relays, which is fine. In the following test, we consider connecting overload1, which uses overcurrent relay1 to respond. In the next test, we connected overload4 after the transformer, which caused protective relay1 to react and trip at the set time. If we connect overcurrent4 behind busbar M3 and re-run the simulation, the overcurrent relay2 will react. This change confirms the correct operation of selective tripping.

The second testing of overcurrent relays will consist of testing the second stage for short circuits. In the first model situation to test the functionality of the models, we consider a connection load5 on which a short circuit will occur. The result of the test is that overcurrent protection relay2 reacted due to a higher measured current than was set on the individual protection relays, whereas overcurrent relay2 was set to have a shorter action time, so it tripped selectively first. In the next test, we create a short circuit on the transformer and re-run the simulation, but now the overcurrent relay1 will trip because the overcurrent relay2 does not detect the fault. If we connect Load2 to which the short circuit is created, no protection will react because it is a short circuit outside the protected area. This change confirms the correct functioning of the selective tripping for the second short-circuit stage.

The last testing of the overcurrent relays will consist of testing the directional member for short circuits, as also shown in Fig. 15. In the first model situation to test the functionality of the models, we consider a connection Load5, on which a short circuit will occur. The result of the test is that the overcurrent protection1 reacted due to the same short circuit current direction, whereas the overcurrent relay2 did not react due to the blocking of the directional member, which is in the opposite direction. In the next test, we will create a short circuit on the transformer and connect busbar M1 and M3. We run the simulation again, but now both overcurrent relays have tripped because the conditions on both protections are met.

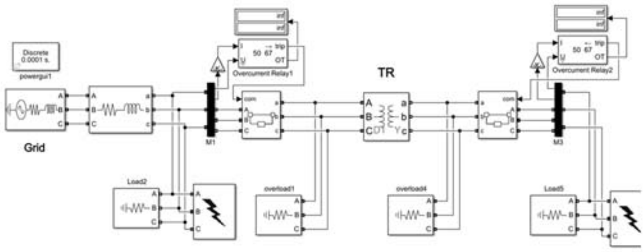


Fig. 15 Directional test of overcurrent protection models

This test confirms the correct operation of the directional link in the overcurrent protection model. The test results confirm that the protective relay model works reliably and correctly for all simulations. However, the model still has many shortcomings that will be eliminated in the future, such as the intercommunication between the protective relays.

4.2. Model of differential protection

The differential protection model was created as a supplement to overcurrent protection, and it is a simple model, as shown in Fig. 16, that can be extended by overcurrent protection, which is currently not available. The principle of differential protection is very simple, it is the difference between current vectors at the beginning and at the end of the protected section. The model was designed using the basic parts available from the libraries for Simulink. The protective relay model works on the simple principle of evaluating, based on the input data, whether it is a permissible condition or a fault condition, as also shown in Fig. 18. The input data is the current inputs from the measurement by which the trip delay is evaluated. The measurement data type is current vector (complex number). The model considers an ideal current transformer conversion.

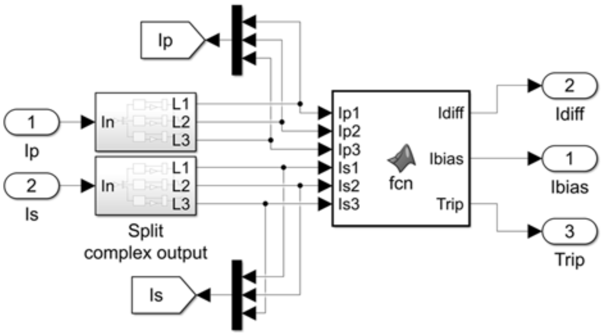


Fig. 16 Schematic model of differential relay.

The model has only current inputs Ip (Input or start of the protected area) and Is (Output or exit of the protected area) as shown in Fig. 17. Furthermore, the model has three outputs for output to the TRIP circuit breaker output Ib (displaying the value of the balance current), Id (displaying the value of the differential current). The model has a display of the set function according to the ANSI code as shown in Fig. 17.

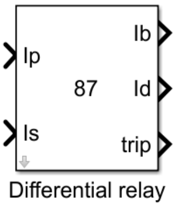


Fig. 17 Model of differential relay

The calculation of the tripping characteristic for a differential relay is according to equations (2) to (4).

$$I_d = |\bar{I_P}\times TAP - \bar{I_s}\times TAP| \tag{2}$$

$$I_b = \frac{|\bar{I_p}\times TAP| + |\bar{I_s}\times TAP|}{2} \tag{3}$$

$$TAP = \frac{S}{\sqrt{3}\times U_{L-L}}\times CT \tag{4}$$

Where:

I_d represents the differential current (A),
I_P is a vector of the incoming current into the area (A),
TAP is the current transformer compensation factor (A),
I_S is a vector of the outgoing current from the area (A),
CT is the conversion ratio of the current transformer (-),
S is transformer performance (VA),
U_{L-L} is the potential of line to line (line voltage) (V),

The model requires fundamental data for setting the differential protection like unrestrained element operating current, restrained operating current, restraint slope 1 and

2, and restrain current slope limit to slope 1. The CT setting retains similar requirements as the overcurrent relay with a different setting TAP value to compensate for different CT and their transfers. Especially when the differential protection relay is used to protect the distribution transformer. In the case of line protection, TAP can be considered a real transfer of CT. Equation (4) will have the following form: TAP = CT. The tripping characteristic of the differential protection is shown in Fig. 18. The characteristic shows that much more data must be entered than for overcurrent protection, while the new protection can already calculate some of the values themselves, as has been implemented in this model. For plotting the characteristics, it is necessary to have the individual parameters calculated as I_{b2-4}, I_{d2-4}, SLP_1 (slope 1), and SPL_2 (slope 2).

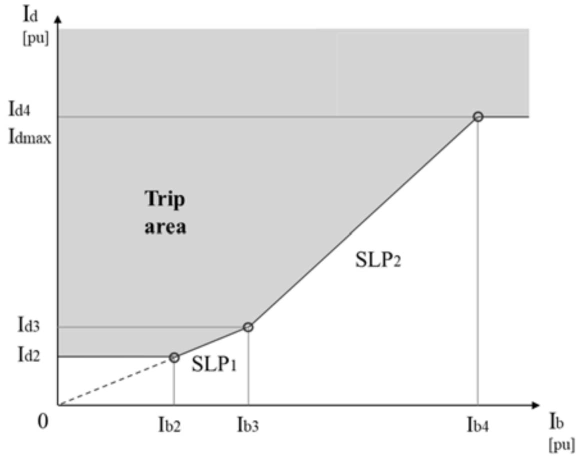
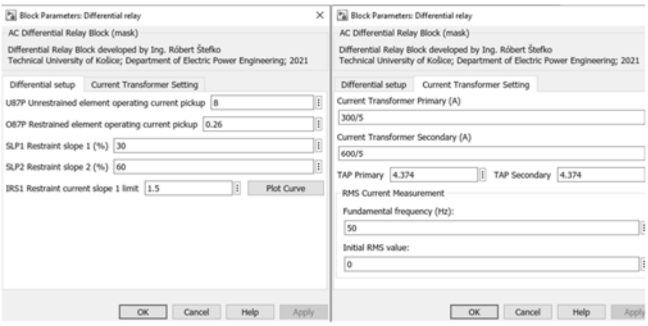


Fig. 18 The tripping characteristic of the differential protection



Block Parameters: Differential relay

AC Differential Relay Block (mask)

Differential Relay Block developed by Ing. Róbert Štefko
Technical University of Košice; Department of Electric Power Engineering; 2021

Differential setup | Current Transformer Setting

U87P Unrestrained element operating current pickup: 8
O87P Restrained element operating current pickup: 0.26
SLP1 Restraint slope 1 (%): 30
SLP2 Restraint slope 2 (%): 60
IRS1 Restraint current slope 1 limit: 1.5

Block Parameters: Differential relay

AC Differential Relay Block (mask)

Differential Relay Block developed by Ing. Róbert Štefko
Technical University of Košice; Department of Electric Power Engineering; 2021

Differential setup | Current Transformer Setting

Current Transformer Primary (A): 300/5
Current Transformer Secondary (A): 600/5
TAP Primary: 4.374
TAP Secondary: 4.374
RMS Current Measurement
Fundamental frequency (Hz): 50
Initial RMS value: 0

Fig. 19 Differential protection setting options

While during the actual setting, only U87P is entered, which represents i_{d4} (I_{dmax}), O87P, which represents i_{d2}, IRS1 (restraint current slope 1 limit), which is determined from the range of 1.5 to 2.5, and the percentage value for SLP1 and SLP2. These input parameters are shown in Fig. 19.

The slope for SLP1 is calculated from the error rates of individual parts, such as CT transfer errors, excitation current, protection transfer errors, safety margin, and relay errors. The sum of these percentages, which vary depending on the parts used, is around 30 %. For slope 2 (SLP2), it is recommended to set a slope value of twice the amount of 1 for CT false current. To better understand why the differential protection has this shape, the fault characteristics of some parts are added to the tripping characteristics of the differential protection, as shown in Fig. 20.

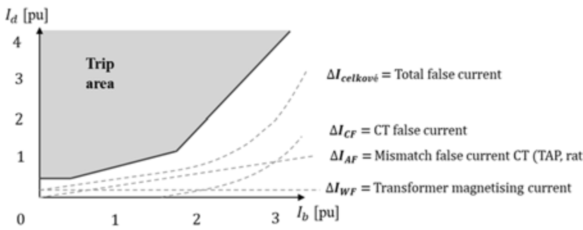


Fig. 20 The tripping characteristics of the differential protection

The differential relay model was tested on the simple example shown in Chyba! Nenašiel sa žiaden zdroj odkazov., which consists of a power supply, one transformer (TR), a load (Load5), a power line, and two circuit breakers. The first differential protection test will consist of a normal operation state. The first model situation to test the functionality of the model, we only consider the Load5 connected. In the result of the test is that the protection relay did not respond due to a lower measured current than was set up at the protection relay, which is fine. In the following test, we consider the connection of an overload4 on the secondary side of the transformer, which will cause a reaction and subsequent tripping of the differential protection relay. In the next test, we connected an overload1 to the primary side of the transformer, which caused the protective relay to react in the same way. Such protection action confirms the correctness of the differential protection action for the occurrence of increased losses on the transformer, which may be a sign of partial discharges and insulation degradation.

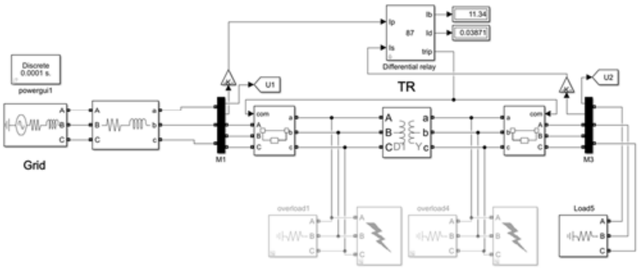


Fig. 21 Test setup of differential protection model

The second testing of the differential protective relay will consist of testing for short circuits. Consider a Load5 connection where a short circuit occurs on the secondary side of the transformer. The result of the test is that the differential protective relay reacted due to a higher differential current than was set on the protective relay. In the next test, we create a short circuit on the primary side of the transformer, leaving the Load5 connected in the same way and run the simulation again. The protection will react in the same way because the short circuit still occurred in the protection zone. If we move the short circuit location in front of the M1 busbar, the differential protection will not react anymore because it is a short circuit outside the protected zone.

5. CONCLUSIONS

The issue of designing a protection system for RES microgrids requires increased attention due to the penetration of large numbers of RES into distribution networks. The purpose of RES is mainly to reduce short circuit currents, which makes the design of the protection system even more challenging. The purpose of this paper was to highlight the acceleration of research using Matlab and Simulink simulation environments in which models of different protection relays have been created which will be used for further research. This paper sought to promote research on protection relays that will be deployed in the future in microgrids for low voltage levels. Since these are the first versions of both models, they still need to be fine-tuned to be more like real digital protection relays, especially from the point of view of measurement and mutual communication.

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