Kaunas University of Technology

Faculty of Electrical and Electronics Engineering

Adaptive Protection in Smart Grids

Master's Final Degree Project

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Kaunas, 2021

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Adaptive Protection in Smart Grids

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Summary

The past decade has seen the sudden rise of renewable generation all over the world and many countries have introduced policies to combat the climate crisis. Only a few utility firms, however, have engaged in research into the impact of renewable energy on the current power grid. Even those studies were primarily concerned with the power system's stability and dynamics, with little attention paid to the impact of power system protection changes owing to low inertia generation, not to mention the lack of interest in distribution systems. Using new communication technologies at the distribution level has become fairly popular. The cost of digitizing the existing substation has substantially reduced over the years and this has encouraged the utilities to focus more on distribution automation while only basic protection functionalities are being implemented.

It is more economical and efficient to address the problems associated with the protection in existing infrastructure, as implementing an entirely new set of protection hardware will incur huge financial capital investments. So, adaptive protection is one of the best suitable solutions as it can effectively work on existing smart grid architecture. The requirement, implementation and advantage of this scheme are discussed in detail as part of this thesis.

Many distribution companies use a power system analysis software such as ETAP / DIgSILENT to evaluate the protection system settings for their network. For the implementation of Adaptive protection, revised settings will be calculated for any major changes in the topology of the primary network using the same software and these settings will be stored inside the appropriate numerical relays as different group settings. IEC 61850 communication architecture can be used to detect the changes in topology or operation parameters of the network and subsequently the relevant group settings will be activated by Adaptive protection.

The same philosophy is implemented on a distribution network from Alytus substation area and with the help of the Python API feature of the Powerfactory Adaptive protection, the algorithm was checked for different scenarios of DER integration in the network. The key element to detect DER integration in this project is implemented with the help of monitoring the breaker ON and OFF states. Using RMS simulations inside the python IDE environment the performance of the algorithm is validated. This process resembles the real-time simulation; however, it is not to be treated as equivalent to a real-time process as the calculations performed in RMS simulations are different from an actual real-time simulator. This theory may be thoroughly validated in laboratories using hardware in loop testing, such as the RTDS simulator or any similar. The same network can be constructed in these simulators, and a real-world numerical relay can be used to evaluate the scheme's operation and reliability in the event of integration errors.

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Santrauka

Pastarąjį dešimtmetį visame pasaulyje staiga išaugo atsinaujinančių išteklių gamyba ir daugelis šalių pradėjo kovos su klimato krize politiką. Tačiau tik kelios komunalinių paslaugų įmonės tyrė atsinaujinančios energijos poveikį dabartiniam elektros tinklui. Visgi tie tyrimai pirmiausia buvo susiję su energetikos sistemos stabilumu ir dinamika, mažai dėmesio skiriant elektros sistemos apsaugos pokyčių poveikiui dėl mažos inercijos generavimo, jau nekalbant apie nesidomėjimą paskirstymo sistemomis. Naujų komunikacijos technologijų naudojimas platinimo lygiu tapo gana populiarus. Metams bėgant esamos pastotės skaitmeninimo kaina iš esmės sumažėjo ir tai paskatino komunalines įmones daugiau dėmesio skirti paskirstymo automatizavimui, kol įgyvendinamos tik pagrindinės apsaugos funkcijos.

Yra ekonomiškiau ir efektyviau spręsti problemas, susijusias su esamos infrastruktūros apsauga, nei įdiegti visiškai naują apsaugos įrangos rinkinį, kuriam bus reikalingos didžiulės finansinio kapitalo investicijos. Taigi, pritakomoji apsauga yra vienas iš geriausių tinkamų sprendimų, nes ji gali efektyviai dirbti su esama išmaniojo tinklo architektūra. Šios schemos reikalavimai, įgyvendinimas ir pranašumai išsamiai aptariami šioje disertacijoje.

Daugelis paskirstymo kompanijų naudoja tinklo sistemos analizės programinę įrangą, pvz., ETAP / DIgSILENT, kad įvertintų savo tinklo apsaugos sistemos nustatymus. Naudojant pritaikomąją apsaugą bus apskaičiuoti pataisyti nustatymai visiems pagrindinio tinklo topologijos pokyčiams, naudojant tą pačią programinę įrangą ir šie nustatymai bus saugomi atitinkamose skaitmeninėse relėse kaip skirtingi grupės nustatymai. Naudojant IEC 61850 ryšio architektūrą galima nustatyti tinklo topologijos ar veikimo parametrų pokyčius, o vėliau bus suaktyvinti atitinkami grupės parametrai.

Ta pati filosofija yra įgyvendinama paskirstymo tinkle iš Alytaus pastotės teritorijos ir naudojant „Powerfactory Adaptive“ apsaugos „Python“ API funkciją, algoritmas buvo patikrintas dėl skirtingų DER integravimo tinkle scenarijų. Pagrindinis elementas DER integracijai aptikti šiame projekte įgyvendinamas stebint pertraukiklio įjungimo ir išjungimo būsenas. Naudojant RMS modeliavimus python IDE aplinkoje, algoritmo našumas patvirtinamas. Šis procesas primena realaus laiko modeliavimą; tačiau jis neturi būti traktuojamas kaip lygiavertis realaus laiko procesui, nes RMS simuliacijose atlikti skaičiavimai skiriasi nuo realaus laiko simuliatoriaus. Ši teorija gali būti kruopščiai patvirtinta laboratorijose, naudojant aparatinę įrangą atliekant kilpų bandymus, pvz., RTDS simuliatorių ar bet kurį panašų. Šiuose simuliatoriuose gali būti sukurtas tas pats tinklas, o realaus pasaulio skaitmeninė relė gali būti naudojama schemos veikimui ir patikimumui įvertinti integracijos klaidų atveju.

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Abbreviations

ADA	Adaptive Protection Architecture
ADP	Adaptive Protection
API	Application Programming Interface
ALF	Accuracy Limiting Factor
CT	Current Transformer
CB	Circuit Breaker
CTR	Current Transformer Ratio
DER	Distributed Energy Resource
DG	Distribution Generation
DIgSILENT	DIgital SImuLation of Electrical NeTworks
DSL	DIgSILENT Scripting Language
DT	Definite Time
ESS	Energy Storage system
EMS	Energy Management System
EI	Extremely Inverse
EV	Electrical Vehicle
EMT	Electro Magnetic Transient
ETAP	Electrical Transient Analyzer Program
FLA	Full Load Amperes
GTP	General Technical Particulars
GUI	Graphical User Interface
HRC	High Rupturing Capacity
IDE	Integrated Development Environment
IDMT	Inverse Definitive Mean Time
IED	Intelligent Electronic Device
LVCB	Low Voltage Circuit Breaker
OEM	Original Equipment Manufacturer
OCR	Over Current Relay
PCC	Point of Common Coupling
PV	Photo Voltaic
PSSE	Power System Simulator for Engineering
RES	Renewable Energy Source
SCADA	Supervisory Control And Data Acquisition
TMS	Time Multiplier Setting
TOC	Time Overcurrent Curve

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Introduction

Objective

The aim of this project is to use an adaptive protection scheme to address protection challenges that develop as a result of the integration of new renewables at the distribution level. The scheme's architecture is expected to be applied in a smart grid environment. Existing numerical relays that function with communication architecture will be modified as part of the proposed method, with no new hardware being added. The scheme must be created in a simulated environment using appropriate tools.

The following important tasks are involved in the overall research project.

- Conducting a research literature review for understanding of the adaptive protection scheme and protection related issues with DER integration at distribution level.
- Identifying and obtaining a thesis license to a simulation software and tools for the development of adaptive protection. Powerfactory from DIgSILENT and Python are utilized in this project.
- Data from the distribution system is collected in order to model it in software. This project makes use of a 10kV distribution infrastructure from the Alytus area.
- Modeling the distribution system in Powerfactory and conducting load flow and short circuit investigations to ensure that the model is error-free and capable of being used for investigation of case studies.
- Designing a protection system and conducting relay coordination studies to ensure that the simulated distribution system's protection system is in working order.
- Identifying weaknesses in the network and studying concerns connected to network protection with the incorporation of renewable energy sources.
- Executing RMS simulations with simulated renewables to better understand how the protection system behaves in faulted conditions and calculating revised relay settings for the new topology.
- Designing adapting protection with the help of Python API and performing RMS simulation studies and plotting the results.
- Documentation and analysis of findings after the script has been fine-tuned to an appropriate level of accuracy.

Background

The electric power system can be summarised into three major parts, such as generation, transmission, and distribution. Generation is where the primary energy is being converted to electrical energy and is transported via transmission to the consumers at the distribution level. The goal of the power grid is to facilitate electrical energy transportation from the generation location to the consumer while maintaining acceptable reliability and voltage quality. To reduce the electricity prices, many countries since the early 90s opened their electricity market and made it easier for many new investors to start electricity generation. In addition to that, the major focus on reducing carbon emission and greenhouse emissions in electricity generation has encouraged to focus on cleaner energy production technologies. The shift from large conventional bulk generation to small distributed renewable electricity production is the new reality of the electricity system.

Conventional bulk electricity production is connected at a higher and extra-high voltage level, whereas small-scale generation such as renewable energy is connected at medium and lower voltage level. This shift would not only result in a complicated power grid network that is not designed for handling these sudden changes, but it would also add the element of difficulty in electricity production prediction. The major challenge for power engineers with renewable energy integration is a power grid network with low inertia generation that could result in instability during major power disturbances. However, the focus of this thesis is on protection philosophy and the challenges associated with drastic changes in network topology, so, the stability and state estimation are out of the scope.

New developments in production technologies are one of the major reasons behind the sudden surge in PV plants and windmills in electricity production. This ensued accelerated growth of renewable generation at medium and low voltage levels. As shown in Fig.1 [1], the growth of installed renewable energy capacity has grown exponentially in the past decade. This has eventually resulted in the rise of distributed energy resources (DER) integration at the distribution level. The DER, also referred to as distribution generation (DG) is a small-scale technology to produce electricity close to the

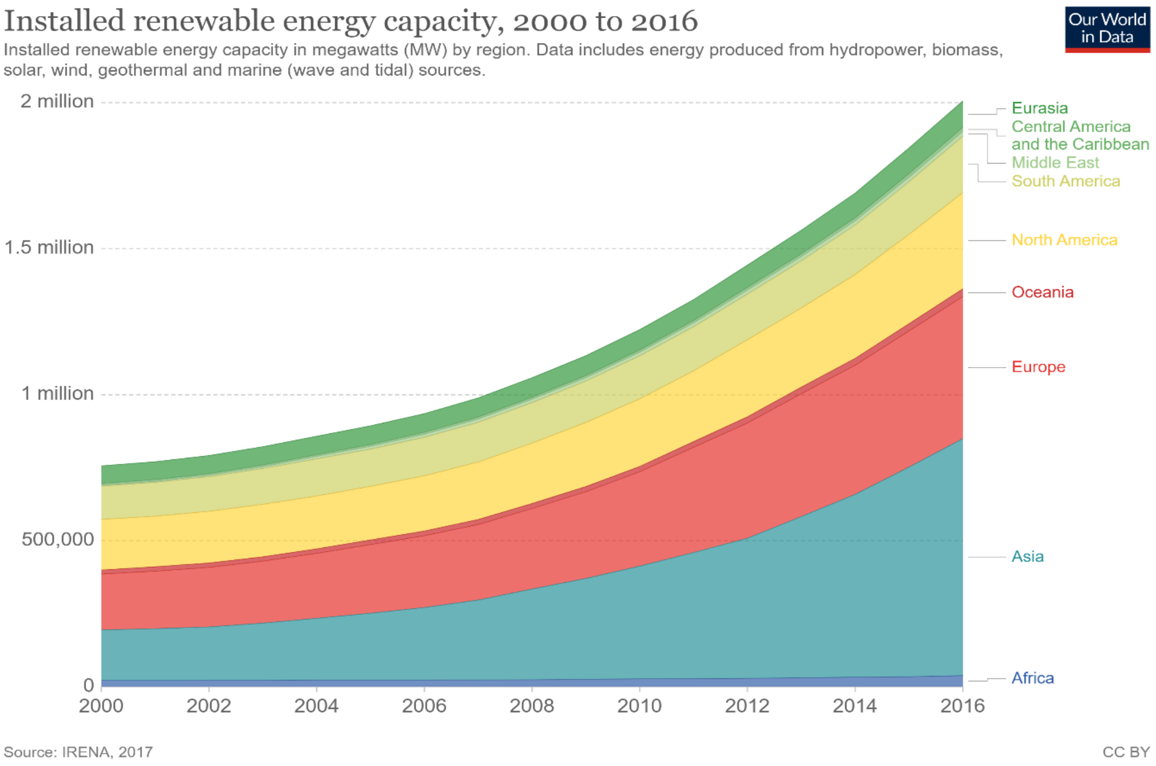


Fig. 1. Installed renewable energy capacity growth from 2000 to 2016 across the world [1]

consumers, in most cases, these generations would be either a small-scale wind farm or a PV generation or it could be a Diesel generation unit as well.

Power Distribution

Electricity access across the world has been steadily increasing. As it can be seen from the chart shown in Fig. 2 [2], people living without electricity has fallen below 15% of the total world population. In this context, it is very important to plan the distribution system very efficiently to assure that the growing electricity demand can be satisfied. The primary objective of the distribution networks is to serve consumers by transfer of energy received from the primary transmission system. And the distribution system planning is to ensure that the increasing demand in terms of new consumers and loads at high load densities can be satisfied efficiently by adding necessary additional distribution substations. In simpler terms, the planning process has to begin at the consumer level. The load, load factor, and other load characteristics will decide the type of distribution system to be built. When the loads are decided, they are grouped for service to be connected at the distribution transformer. These loads on transformers determine the primary distribution system demand and thereby deciding the location of transmission substations.

The rise in renewable energy integration at low and medium voltage level has prompted challenges for conventional protection architecture. The fault contribution and bi-directional power flows from localized DER at the distribution level has an enormous effect on existing relay coordination. Distribution grids are radial (or sometimes ring) in model and mostly designed with a single-point feeding based on non-directional relays, this poses the risks of maloperation in bi-directional power flow conditions.

During normal service, i.e., when connected to the grid, this could lead to compromised relay coordination and a nuisance or delayed tripping. Even in the case of microgrids that work in island operation, it is a more demanding situation from a protection point of view, as the short-circuit currents fed by DER are very low and the dynamics of Diesel Generators are sensitive to faults.

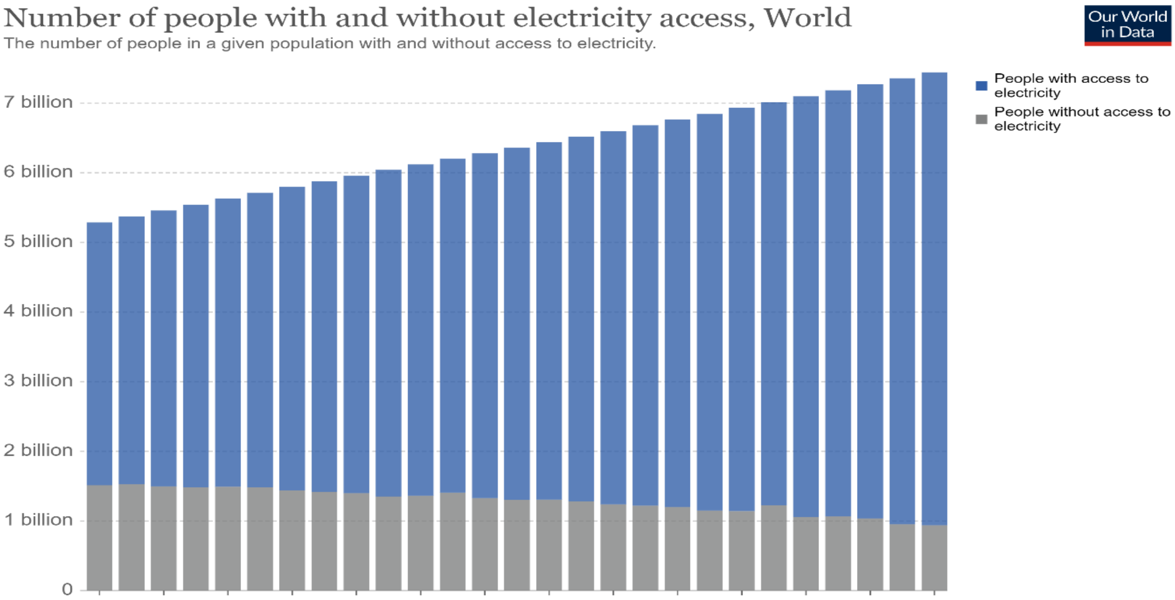


Fig. 2. Number of people with and without electricity from 1990 to 2016 across the world. [2]

Therefore, protection adaptation to different topology changes will be more and more often required in future distribution networks.

Smart Grid

The most crucial and important problems faced by the world after the industrial revolution is notably the energy crisis. Traditional energy resources, such as coal, and gas have resulted in increased environmental pollution. And the power demand and generation have always had unprecedented growth among each other, the demand for power in the developing world and the drive to curb carbon emissions has caused un-matching importance for renewable generation in the power industry.

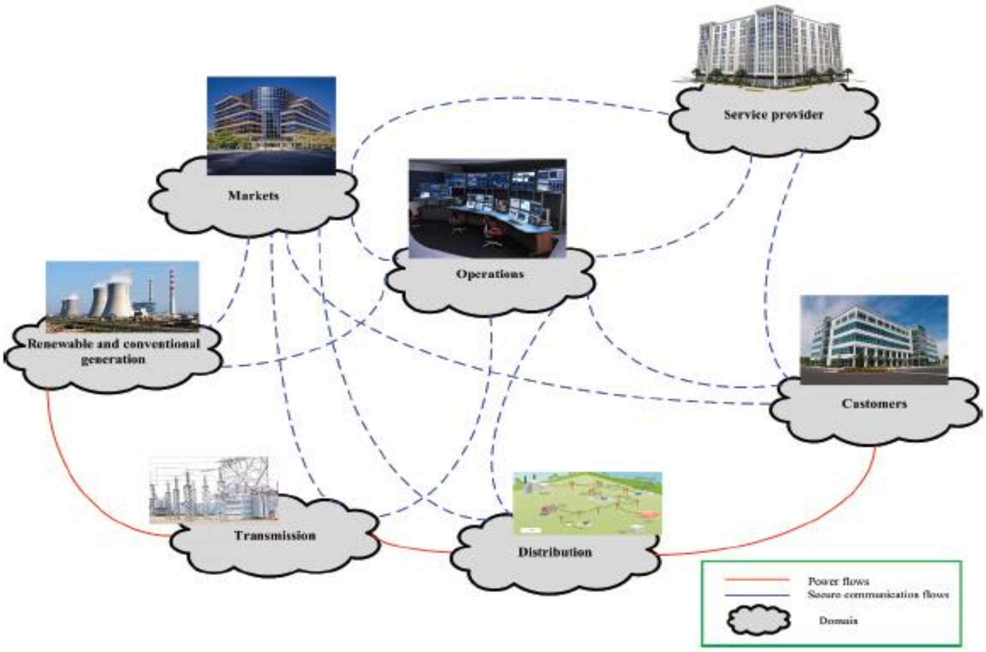


Fig. 3. Components of smart grid system [3]

The prime motive for many utilities to replace the conventional power system with the smart grid is to have better control over the grid. In addition, the self-healing feature of the smart grid will enable them to avoid constructing new power stations, substations and T&D lines, there by reducing costs on new projects. This allows the utilities to utilize the existing system efficiently and allows consumers to get their sources of power from wind, solar and other green resources. The philosophy of a smart grid allows to take advantage of new technologies, such as plug-in electric vehicles, various types of distributed generation and many others. These technologies have transformed existing power system facilities to be more robust, dependable, and effective. Another worth mentioned feature of smart grids is effective integration and utilisation of Energy Storage Systems (ESS), over the years manufacturers have improved the technologies of the ESS to allow sudden change of energy requirements of consumers and is being used as an effective method to store energy.

A smart grid is an electric grid that efficiently monitors customers behaviours and actions with the help of network automation and controls to delivers economic, sustainable power efficiently in a secure way. As shown in Fig.3 [3], Transmission & Distribution system, service providers, Markets, generation, and consumers are the major elements of an efficient smart grid. An efficiently working smart grid can reduce the number of power outages and increases the reliability of the power supply to the grid. With the help of intelligent solutions in the smart grid, the hosting capacity of the network for renewable resources integration can be increased further.

Smart grids can facilitate many kinds of generations and consumers simultaneously due to their flexibility. These included with many more advantages of smart grids are the reasons behind advancements in up-gradation and replacement of existing conventional power system. This integration of power, communication and control technologies into the conventional power system allows unrestricted power flow and information exchange within the system at a greater level of coordination and thereby achieving effective control of the power system.

In recent years smart grids become the new focus, the strong communication backbone of the smart grid system is important for load dispatch centres to acquire fault information from protection relays and disturbance recorders located at different parts of the power system. However, a traditional EMS/SCADA system may not have the capability to analyse the information on its own. So, a new protection strategy is required to maintain acceptable protection performance. An Adaptive protection philosophy is being discussed in this project as a prominent solution to enhance the performance of smart grid networks with DER systems.

1. Distribution system

The electrical power distribution is further divided into two major sub-categories, commonly referred to as primary and secondary distribution systems. A primary distribution system is the part of an electric utility system located between the distribution substation and the distribution transformers, whereas the secondary distribution system is the network of consumers connected at the secondary side of the distribution transformers. In simple terms, it can be understood that the network on the primary side of the 'Distribution transformer' can be referred to as the Primary system, while the secondary distribution system is connected to the secondary side of it. However, this understanding of distribution classification may not be the same for every utility as many have their own definition of terminology. One such is being followed by many utilities across the world, is based on the voltage level of the network, operating voltage of 10kV to 33kV is considered as Primary distribution system. To understand the protection related issues as part of this thesis, a primary network is simulated and studies are performed, the voltage level of this network is 10kV, which is the common primary distribution level in Lithuania. Given this, the discussion of the secondary system is not emphasised, however, the network structure discussed for primary can be applied to secondary type as well.[4]

1.1 Radial type distribution system

The radial type of network is one of the easiest and least expensive distribution systems, making it the most common type of primary feeder network type used in many distribution systems around the world. Here, Fig.4 [5] shows the typical arrangement of a radial type distribution system. In this network, the main primary feeder splits into many primary laterals, which then split into multiple sub-laterals to service all distribution transformers. It should be observed here that, in a distribution system, a feeder which usually means a three-phase four-wire circuit, branches are either single-phase or three-phase circuits tapped off the main feeder. [6]

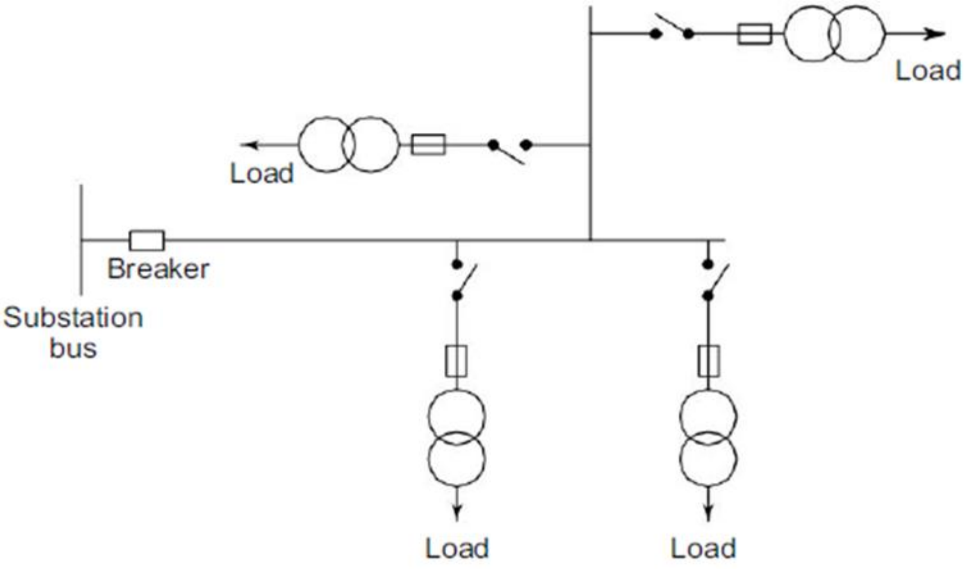


Fig. 4. Typical radial type distribution system arrangement [5]

The magnitude of the current is highest at the main feeder, the load current is relatively less for branches as the sizing of the sub-feeders (or branches) is dependent on the load connected to it and the current levels changes as the load connected to the feeders vary, this implies that the size of the main feeder is always higher than the branches. However, even though the load on the feeder is less, the utilities cannot reduce the size of the conductor as they have to follow the permissible voltage regulation, and this is to avoid voltage drops for the tail end customers. This could be one of the drawbacks in the radial system, as the consumers connected at the end of the network may face voltage drops during peak loading conditions. There are many ways to improve voltage profile for the far end customers from the main substation, one such system is where the primary feeder connected between the substation bus and the load centre of the service area. This feeder is referred to as an express feeder. Express feeders [6] serve areas farther from the substation and no sub feeders are allowed to be tapped off the express feeder. An alternative way to improve voltage profile is by adding capacitor banks at optimal locations.

The feeders are sectionalized by reclosing devices at different locations in a manner as to isolate the faulted circuit as little as possible to hamper power supply to as few consumers as possible. Since it is very uneconomical to provide reclosers to every consumer connected to the network, so a trade-off will be decided by the distribution engineers to decide the optimum location for reclosers. And for the rest of the network, fuses will be used in coordination with the reclosers to achieve protection coordination. This highlights that the reliability of service continuity of the radial primary feeders is low. Other than these two type of switching devices, disconnectors are the most common equipment used in radial distribution but due to their inability to break fault currents, they can‘t be considered for protection studies.

1.2 Ring type distribution system

Unlike in radial systems, in ring main distribution system, the primary side of each distribution transformer is connected to two of the adjacent distribution transformers and this forms a loop through, which the primary feeder would return to the bus forming ring type of connection. Due to the nature of this connection, this type of distribution is also referred as loop type distribution system. By achieving a loop in the primary system, each distribution transformers can be fed with two sources of power supply, increasing the reliability of the system in case of any faults in the system, thereby reducing the power outages.

Here as shown in Fig. 5 [4], ring type distribution system is formed by connecting the distribution transformer on a feeder that originated and ended at the same substation bus. Even though the loop connection is established in the primary level of the power system, however, the loop tie disconnect switch is replaced by a loop tie breaker, which is represented as *sectionaliser tie switch* in Fig. 5 [4], this is due to the load conditions and only closed for power restoration in case of fault events. Keeping the ring closed all time would increase the short-circuit level in the system as the loop impedance is much less due to the formation of two parallel fault loops. This type of ring type arrangement is beneficial, especially in cases where high service reliability is important and is being used in applications such as urban distribution, research centres, data centres etc.

The major difference between implementing radial and ring main distribution is, the enormous amount of primary conductor to be used in ring type system as the distance to be covered between each transformer twice, and the size of the feeder conductor has to keep the same throughout the loop as it has to be designed to carry its normal load plus the load of the other half of the loop, this implies the heavy costs involved in developing this type of system. In addition to the excessive conductor requirement, each substation must accommodate two feeder systems to connect in and out ring feeders.

To avoid erroneous tripping and better coordination between the breaker operation periods and in practice, the protection used in ring systems must be directional. Because of the additional voltage transformer card in directional relays, they are more expensive than non-directional relays. However, in a critical application the benefits, such as rapid system restoration, disconnection of the minimum number of consumers outweighs the cost of developing ring systems.

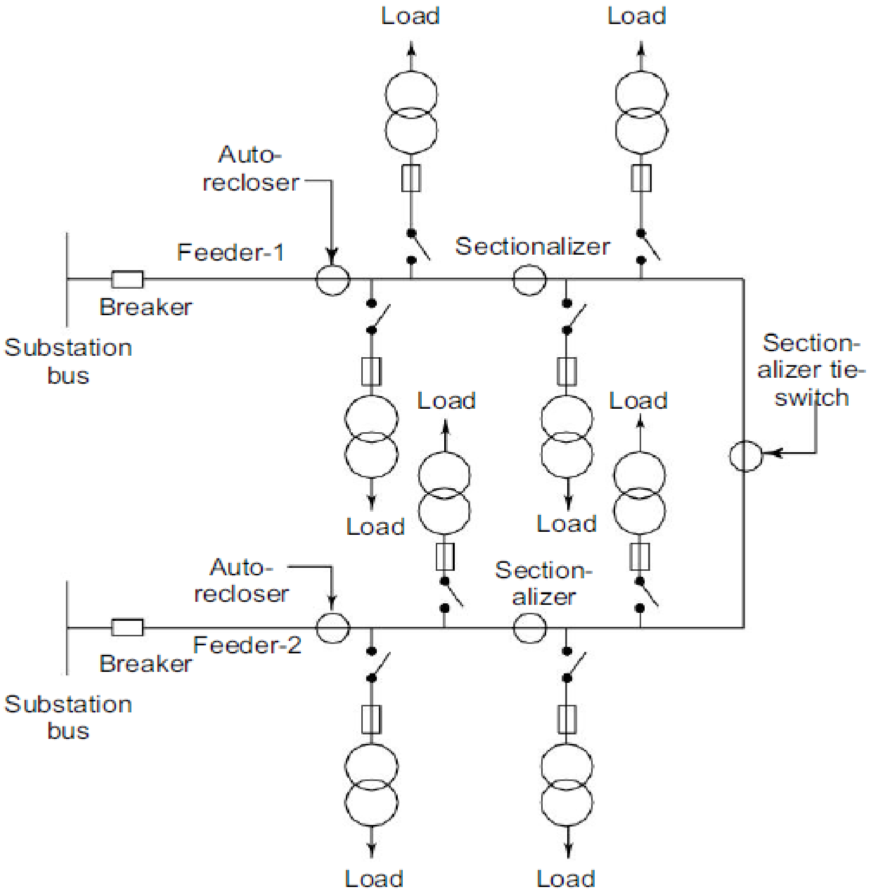


Fig. 5. Typical ring type (or loop type) distribution system arrangement [4]

During the modelling of this project, the distribution network for the area ’Alytus’ (Kaunas County, Lithuania) is being implemented and the network under operation is observed to be predominantly radial, however, in some places, there is a provision to extend supply to the substation from 2 different sources. As the majority of the network is radial, the system is considered as a radial type system for the ease of simulation and calculation, wherever the dual supply provisions are observed, disconnectors are kept open there to achieve more radiality of the network and to reflect practical operation scenarios.

1.3 Protection in the distribution system

Statistically, distribution systems are more prone to faults due to their weakly coordinated protection and exposure to the environment (in the case of overhead lines). Most of the distributed systems are not provided with active backup protection for economical reasons and this results in false tripping when the main protection fails to operate. The majority of the faults are L-G (Line to ground) in nature, and mostly observed during the monsoon or winter season (due to severe environmental conditions) depending on the region. Irrespective of the reason behind them, faults would result in heavy flow of currents through the system and causes damages to equipment and in some cases may even result in loss to human life. No matter how perfect the system design is, there will always be faults observed in it, so the main objective of protection philosophy is to protect the power system from these abnormalities as efficiently as possible, here efficiency should read as selectivity and reliability.

The IEC standard defines a protection system as a complete arrangement of protection equipment and other devices required to achieve a specified function based on a protection principle. Protection Equipment is a collection of protection devices (relays, fuses, etc.). devices such as CT, CB, Contactors are not considered as protection devices as they cannot decide unhealthy conditions of the power system. To fulfil the protection requirements with optimum speed for various configurations, operating conditions, and construction features, it is necessary to have different types of relays that respond to various functions of the power system quantities. For instance, in a distribution system, the most common element is the distribution transformer, by monitoring the magnitude of the current drawn, the protection of the transformer can be achieved. Current transformers are the crucial devices to detect these currents at different voltage levels and they are extensively used across the power system.

Based on the type of functionalities, protection devices can be very expensive, like distance relay that are embedded with complex algorithms and extended functionalities. So they are mostly used in a critical part of the power system like sub-transmission and transmission networks. For utility companies that are operating distribution system, optimising the installation and operation costs is very essential. Relays such as distance and differential can be seen as very expensive to use, so a more affordable and efficient protection function called ‘over current’ protection is used. Overcurrent protection works on the principle of detection of exceeding current above the threshold limit. This threshold is also referred to as ‘Pick-up’ current. There are different ways to achieve this functionality in the application, either with the help of relays or with the help of fuses, both these devices are discussed here in brief for ease of understanding.

1.3.1 Current transformers

In an electric circuit, when the values of current and voltages are too high to measure with a direct connection, a coupling transformer is used to convert the values to the measurable range, these transformers are referred to as *instrument transformers*. A current transformer is a type of instrument transformer, that works as a step-up transformer and replicates the current in the primary circuit at the instrument level. IEC defines current transformers as *an instrument transformer in which the secondary current, in normal conditions of use, is substantially proportional to the primary current and differs in phase from it by an angle which is approximately zero for an appropriate direction of the connections.* [7]

Based on the application, current transformers can be broadly categorized into the following categories,

- Measurement CT - used for measurement purposes.
- Protection class CT - used in major protection applications.
- Special protection class CT - for special protections such as differential protection.

This classification is not only based on application, but it also informs us of the ability of the current transformer to replicate the primary current signal with less distortion during a fault condition. For instance, measurement transformers are not designed to measure fault currents and hence will have a heavily distorted secondary signal during fault condition due to saturation of the magnetic core of the CT. Since the research is only focused on, protection aspect of the distribution, protection class CT is discussed in brief for understanding.

Several factors play a key role in selecting a CT during the design phase. However, not every parameter is related to the protection aspect, for example 'altitude above sea level' can be ignored for protection-related studies. Because of this, the following major specifications are focused on during this project due to their importance in relay coordination studies.

- Primary rated current
- Secondary rated current
- Accuracy class
- Accuracy limiting factor.
- Apparent power.
- Rated short circuit current (for 1sec)

The value of the designed rated current for the continuous operation is referred to as *rated primary current*, and the values of this parameter are standardized for users to select. According to IEC, these values must be either equal to or multiples of 10, 12.5, 15, 20, 25, 30, 40, 50, 60 and 75A. The value of primary rated current should be at least 10% higher than the maximum operating current expected. This is to allow continuous operation during overload conditions. And the operating current should not fall below 25% of the rated operating current and this is to avoid composite errors due to magnetizing current at lower operating ranges.

According to both IEC and IEEE, the secondary rated currents are fixed at either 1A or 5A and most of the designers prefers to use 1A secondary due to the less burden caused by the connecting cables and secondary equipment on CT. For example, A loop resistance of 1Ω would result in a burden of 1 VA (I^2R) for a 1A secondary, whereas 25VA for 5A secondary, resulting in a higher VA burden for CT.

Protection class current transformers, also known as 'class P' current transformers must preserve minimum accuracy of the converted signal during a fault condition, this is defined as Accuracy Limiting Factor (ALF) and is decided based on the fault level at the connecting point of the CT. For instance, a 5P20 specification of CT is to be interpreted as ±5% accuracy (composite error) when 20 times of rated current is in the primary circuit and is referred to as ALF.

The burden of CT is usually expressed in apparent power and interpreted as the highest amount of secondary impedance that a CT can drive at rated current without losing its accuracy. The value of the CT burden is decided based on the number of instruments that the CT would be connected to and the resistance of the connecting cables in the secondary circuit. With all the modern numerical relays having the lowest input impedance, the secondary burden can be as low as 25% of the rated burden. These would result in CT operating at higher ALF than the designed one. For the cases where the secondary connected burden is lower than the rated, the ALF would be recalculated using the following relation,

$$\text{Calculated ALF} = \text{Rated ALF} \times \frac{S_r + (I_2^2 * R_{ct})}{S_c + (I_2^2 * R_{ct})}$$

S_r - Rated burden in VA

S_c - Connected burden in VA

I_2 - Secondary rated current in A

R_{ct} - Internal CT resistance in Ω

From this relation, it can be clearly understood that the lower the connected burden, the higher the ALF of CT, in other words, the same CT can operate without saturating for a higher short circuit through fault currents. Using this calculated ALF, the sizing of the CT can be optimised during the design stage.

1.3.2 Fuses

Fuses are a form of over-protection device that is commonly used in distribution systems due to their low cost to replace when damaged. IEEE defines *fuse as an over-current protective device with a circuit-opening fusible pat that is heated and severed by the passage of the overcurrent through it*. Fuses are one of the oldest and most basic methods of safeguarding rural networks from faults. The operating time of a fuse varies with the amount of current passed through it; a correctly sized fuse will isolate the circuit by melting out the fuse part and keeping the circuit condition open until it was manually replaced with a healthy one.

There are two types of high-voltage fuse that are in use in distribution systems.

- Explosion type
- Current limiting type

Explosion type fuses are the simplest in construction, as an illustration, a sample is shown in Fig. 7 [6] here. These fuses house fuse link inside a de-ionised fibre coated tube to contain the arc in case of faults. During the fault, a heavy current will flow through the fuse element, causing it to melt down. This fuse element supports the triggers, when it burns the arrangement will open the lock thereby opening the connection physically. The orientation of the drop out fuse is to be interpreted vertically from what is shown in Fig. 7 [6] here. The major advantage of these fuses besides the cost, they are easy to reuse by replacing fuse element, and when they operate, they would provide physical isolation of the circuit.

For indoor distribution substations where using a drop-out fuse is not feasible, a current limiting fuse type is used. Here as shown in Fig.6 [7], the fuse element is enclosed in a tube filled with powder to absorb heat generated during the meltdown. Due to this construction feature, they can support high rupturing capacity, enabling them to be used in point of connection, where a high amount of fault currents can be expected. The disadvantage of these fuses is they cannot provide any visible confirmation of operation unlike explosion type and they cannot be re-used either.

The fuse rating is decided based number of factors, the most important ones are nominal voltage, nominal current, short-circuit capacity. The symmetrical short-circuit capacity of the fuse should be equal to or greater than the symmetrical fault current calculated at the point of the installation. The operation time of the fuse is calculated using the I^2t relation. The characteristics of the fuse operation are close to the Extremely inverse curve of the IDMT relay as shown in Fig. 8 [10]. When two or more fuses are used in the system, the one closed to the load is called the main fuse while the one upstream to that will act as back-up in case the main one fails to operate.

Fig. 7. Explosion (Drop-out) type Fuse [6]

Fig. 6. Current limiting (HRC) type Fuse [7]

1.3.3 Over-current Relay

An overcurrent relay is one of the most common protection used in the protection system, it protects the feeder/equipment under protection by initiating the trip command to the switching device when the current exceeds the pick-up value. Most overcurrent protection devices respond to both, short-circuit or ground-fault current values as well as overload conditions. And these values are decided either from coordination study or from the specification of the equipment. The comparison and selection of operating times are decided for faults at different locations and the proper calculation of OC relay settings is achieved with the knowledge of fault current that would flow at each part of the network. There are three methods to achieve overcurrent relay coordination in protection, and these are coordination by current or by time or the combination of both [10].

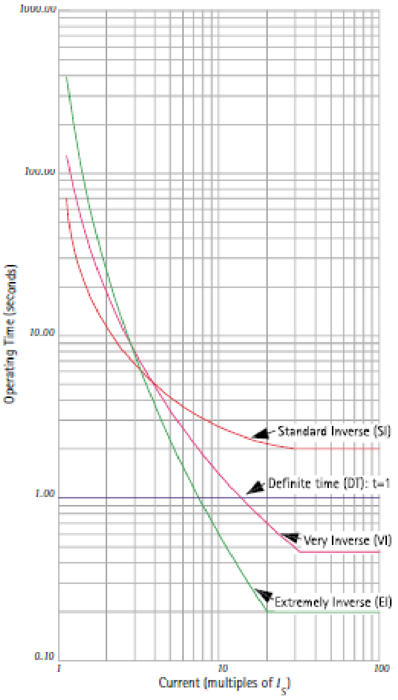
In the *discrimination by time* method [10], a suitable time setting is given to each of the relays controlling the circuit breakers in a power system to ensure that the breaker nearest to the fault opens first. Since the coordination is achieved by discrimination of operating time, these relays are also referred to as *definite time (DT) relays*. To signify their independence of operation from current value these relays are also referred to as *Independent definite time relays*. The major disadvantage of this method is, due to the fixed time of operation even severe faults would take a longer time to clear resulting in damage to the equipment and to the power system as well.[11]

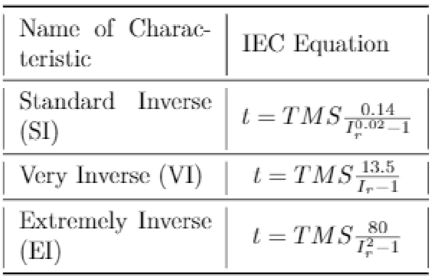
Overcurrent coordination settings in *discrimination by the current* [10] method are typically calculated for the faults closest to breakers. Since the location of the fault on the feeder affects the fault impedance, the fault current will vary. This in turn will result in several coordination issues. So, this method of relay coordination is no longer in use.

The disadvantage of both the above methods is addressed in *discrimination by both time and current* [10] method. The relay characteristics evolved from this has operation time inversely related to current value and the settings are defined for both ’current’, ’time’ and called Inverse time overcurrent relays.

The mathematical relations for each of the curves are mentioned in table Fig.8 [10] and the appropriate curves for a time multiplier setting of 1 second are shown. Even though the curves are only shown for discrete values of TMS, in numerical relays continuous adjustment of TMS is possible. In addition, almost all overcurrent relays are also fitted with a high-set instantaneous element, which is a definite time-based operation. In Fig.8 [10], a standard definite time curve is also shown for illustration purposes.

The most common overcurrent relay characteristics used are *Inverse definite minimum time,* which works on the principle of discrimination by both time and current method. These relays have the advantage of clearing high current faults at shorter operating times. but if a satisfactory grading cannot be achieved, like in the case of coordination of Fuses and relays are required, VI or EI curves may help to resolve the grading issues. Few manufacturers also provide user-configurable curves but the usage of these curves in general practice is very rare.





Name of Characteristic	IEC Equation
Standard Inverse (SI)	$t = TMS\frac{0.14}{I_r^{0.02}-1}$
Very Inverse (VI)	$t = TMS\frac{13.5}{I_r-1}$
Extremely Inverse (EI)	$t = TMS\frac{80}{I_r^2-1}$

Fig. 8. IDMT characteristics for OC relay operation according to IEC [10]

In addition to that, numerical relays will support more than 2 stages of overcurrent relay settings. So, as a common practice, these stages can be used as primary and back protection with different types of setting values, and it is even possible to choose different characteristics to select for both stages. These different group settings provide protection engineers to configure relays for different network conditions.

2. Smart Grid

The advancements in energy production and power transfer technologies have grown many folds over the past century. Renewable energy resources have become more affordable than ever before. This has resulted in the complexity of the utility grid as the generation can be connected anywhere in the system. So, many utilities in developed as well as developing nations are transforming their existing grid networks with better automation and controls to efficiently deliver sustainable, economic, and secure electrical power supplies to their consumers. These networks are sometimes referred to as 'Smart grids'. As the name suggests, smart grid utilizes specially developed technologies that support intelligent monitoring, control, and communication facilities as well as self-healing capability to achieve the objectives of the service providers, such as reduced power outages, the secure power system with less risk from the impacts of terrorism or other sabotage on the grid and maintain reliable, efficient delivery of electricity from generating units to the consumers.

The major advantage of renewable generation over conventional power generation is their unit capacity, RES such as solar (PV) or wind are available from few kW range to multi-MW, as a result in many economies to embrace open electricity markets to take advantage of the flexibility and to shift from the conventional fossil fuel-based power generation. This resulted in more grid-interactive energy generation, which is fundamentally unpredictable. Few of the immediate solutions were given with energy storage, pumped storage and even to use of Electric vehicles (EV) as a storage system, as a part of this project the implications of these changes to an existing system will be studied in detail.

2.1 Distributed Generation

In a traditional distribution system design that has been followed over years involves the power flows from transmission systems to the distribution system. So, both the active and reactive powers flow from high voltage to low voltage, this has been shown in Fig. 9 [12] here. Integration of DER to the distribution system would make the system more active than passive and the power flow can be bi-directional based on the relative magnitude of real and reactive loads and generator outputs. Many utility companies have introduced net-metering and feed-in tariff using the latest smart meters that

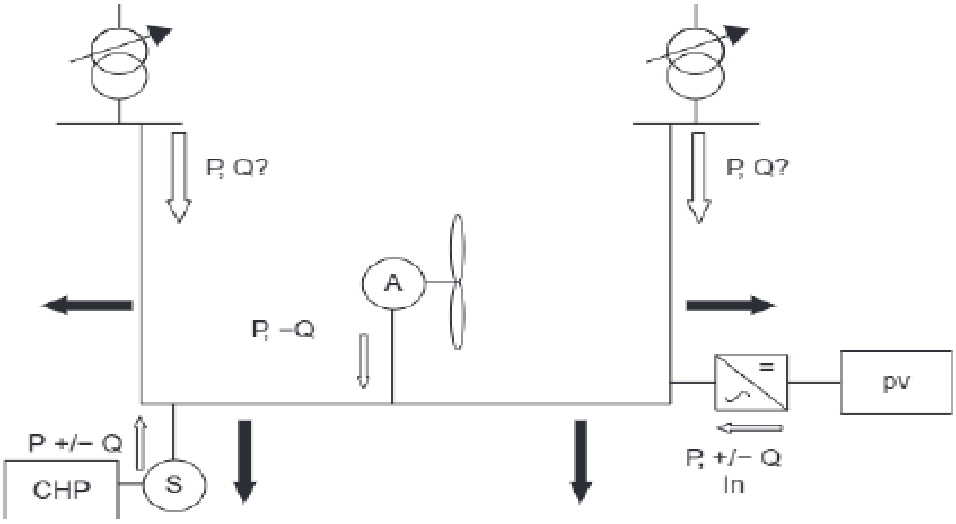


Fig. 9. DER schematic arrangement [12]

record bi-directional power flow, this has encouraged more consumers that are connected to a smart grid to install DERs such as micro wind farm and rooftop PV panels etc. This also benefits the utilities as they have greater generation support and improve the sustainability of energy generation.[12]

A smart grid with DER and ESS, embedded with reliable communication architecture would yield greater flexibility, this enables the grid to be highly effective with real-time control of how the power to be utilized and using intermittent energy from ESS that results in effective exploitation of energy generated.

The connection point of these energy resources to the grid is referred to as *Point of Common Coupling* (PCC) and the operation control architectures are designed for the interconnection of the energy resource with PCC are referred to as *interfacing technologies* and mostly comprised of power electronic devices. Due to the fast-acting nature of power electronics, the fault contribution from these sources is for a limited period but still a significant magnitude in nature. This sudden or unplanned growth in DER at distribution would result in many challenges in protection, which is being discussed further to give the idea on how to address these issues with the help of a novel Adaptive Protection technique.

2.2 Impact of Distributed generation

In principle, the integration of renewable energy sources is the same as bulk powered generators and is based on the same methodology. However, renewable energy sources are geographically dispersed due to their dependency on energy density in environmental conditions. Due to their less energy density and lower amount of generation capacity, they cannot be connected to transmission networks. Any renewable energy generator can work both as a stand-alone or grid-connected system. In stand-alone mode, it would provide for the demand of local loads with or without the help of a storage system in place. On the other hand, a grid-connected renewable energy generator supplies power to a large, interconnected network that is also supplied power by other generators. The connection point is often referred to as the point of common coupling (PCC). Fig 10 [13] here shows the location of PCC with respect to the distribution grid.

Technology using in interfacing equipment would define the power quality of the power being injected at PCC. As the sensitivities of these control architecture may vary depending on the type used and if the local controllability of the distributed generation (DG) is available for the grid operator through smart grid architecture, it would increase the efficiency and reliability of the distribution system. [14]

As shown in Fig 10 [13] here, the interconnection relay oversees the protection aspect of the DG connected to the grid. This relay connection can be connected on either side of the transformer depending on the availability of the space in the switchgear unit. However, using its feeder than at PCC would help to provide power supply to local loads in case the energy source has to isolate from the grid during a fault condition.

In several ways, distributed generation affects distribution network protection. Some effects are the result of an increase in fault current caused by the generator. Other effects arise as a result of a generator's insufficient fault current contribution. One of the most commonly debated implications is the possibility of uncontrolled island activity. The effect of distributed generation on protection is highly influenced by the fault current contribution, and thus by the size and form of the interface.

Synchronous generators have a constant short-circuit current; induction generators contribute for one or two cycles in the case of a three-phase fault and for longer in the case of an unsymmetrical fault. Units with a power electronics interface contribute no or very little to the fault current.

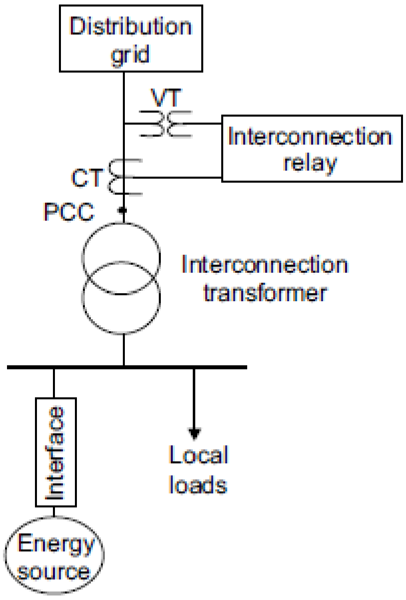


Fig. 10. PCC connection arrangement [13]

Depending on the type of generation and interfacing technology used in DG, the behaviour of the protection would change. In addition to that, network topology also plays a significant role, for instance, fault contribution from DG during low short circuit configurations such as microgrids have a considerable effect on operation than with grid-connected networks.

If the utilities have properly planned and operated, these renewable energy generations may provide benefits to distribution systems by reducing capacity requirements, improving reliability, and reducing losses. So, a distributed generation used properly would improve the service quality of the utility and reduce the operational costs as well.

2.3 Smart grid protection

The decrease in manufacturing cost and availability of better technologies have helped OEMs to produce high-quality relays at affordable cost. And from the last few years, many utilities have experienced high demand in redundant power supply from their clients, this has encouraged them to incorporate these high-speed protection devices that are used to be preferred in high voltage systems in earlier days.

The role of protection in a smart grid is to increase the reliability and to improve the stability of the grid by handling the fault conditions effectively, this will eventually reduce the number of outages and thereby increase redundant power supply to its customers. Additionally, protection devices are the major components of the smart grid that guarantees the isolation of faulted network during disturbances. Protection devices such as relays or reclosers used in smart grids are embedded with the latest state of the art technologies that enable real-time communication with other areas of the power system. This is a very important factor in achieving the self-healing property of the smart grids.

Utilities use the information on faults data from these devices in localizing and identifying the faulted area of the network, results in faster restoration and reduced downtime to the affected customers. These enhanced features result in improved power quality, reduced outages, and voltage fluctuations. However, even these features cannot fully guarantee the integrity of the protection operations, as they do present certain grey areas in their core philosophy itself. This is the main objective and studied in detail further here.

2.4 Protection issues in the distribution system

A conventional distribution network is a passive network and designed to transfer energy received from the transmission system to utility consumers. So, the protection system of the distribution network is designed under the exemption that the power flow is unidirectional. The basic principles followed in the protection philosophy of any systems are, [15, 16]

- *Ensure minimum disruption of supply*: this entails locating and resolving faults as quickly as possible while minimizing disruption to the network's healthy parts. This could be achieved by performing a rigorous coordination study of the system and designing the relay settings of the protection devices accordingly at each voltage level of the network. The drawback of the radial coordination system is that it may result in a large time of operation at the upstream level, but this has can be addressed with fast-acting protection.[15]
- *The fault clearing time should be as low as possible*: faults are expected to be cleared at as minimum time as possible to reduce the damage to equipment resulted from the heavy flow of fault currents. As addressed earlier, depending on the levels of breakers between the generation or source to load, the time of operation could result in higher operating time at up-stream level.[17]
- *Selectivity* of the protection relay for the faults is a very important characteristic of the design as well. For example, the current measurements of the relay should be able to discriminate between a fault and a healthy condition. In a healthy operation, the relay is expected not to initiate any trip signal. Each relay should be able to make this distinction for all fault locations and all types of faults. [13]

In summary, the design of protection for the distribution network is quite challenging even without the presence of DERs in the system. Due to its economical affordability of non-directional overcurrent (OC) relays they the most used and preferred protection in the distribution system. In current practice, most of the OC relays are supplied with both definite and inverse-time curve settings, however, in practice, a directional and non-directional relay vary in cost due to its extra voltage sensor cards. The usage of directional relays is limited to the cases of the ring-main system in the case of distribution networks. Since both types of relays and type of settings has its advantages, the relay settings are to be studied in detail to provide maximum selectivity and efficient operation. [18]

The impact of DER on protection greatly depends on its contribution to faults. When a DER is connected to a distribution feeder, it will change the fault currents and thus jeopardize the protection operation. Protection can fail two ways:

- **Nuisance / Undesired operation**: When a Circuit Breaker (CB) operates (opens) due to trip initiation from the relay when no-fault results in nuisance tripping and isolation of a healthy part of the network.

- **Fail to operate:** Relay is failed to detect the fault and cannot initiate a trip signal to CB but fails to open and results in cascade tripping or instability in the network due to prolonged flow of high fault currents.

Both failures are severe in maintaining the integrity of distribution grid operation but the latter would results in more severe damage to equipment and possible to humans as well. And these could occur even when there is no generation in the network. The failures of the protection system have been further sub-divided and explained in detail here and the same is explained to give an idea of the problems associated with these,[19]

- **Concept failure:** Fail to operate or nuisance tripping due to a compromise made in designing of the system. This could be due to optimizing the design of relays selection, for example, using a non-directional relay in a ring main system could result in complication and nuisance or undesired tripping.
- **Model failure:** A design failure that was already present in the model but not being aware due to either inaccurate or incomplete data. This also includes the changes in the load or topology of the system at a lower level. For these cases, a change in protection settings to be made with the updated study of relay setting calculation, fail to do so can be seen as a model failure.
- **Setting failure:** This could be the most common failure, resulted from human errors in the configuration of relays or altering the relay settings with poor knowledge of the device. It is the Failures of the protection due to the relay setting not being equal to the actual design setting.
- **Device failure:** Failures of a protective system due to equipment damage, damage of sensing equipment (Instrument transformers), protection device (Relays) or the switching elements (Circuit breakers) that result in unwanted or no operation of protection. This might have resulted from poor maintenance and asset integrity records of the utility, which could be addressed by more periodic checking and maintenance of the devices.[20]

Among the protection failures discussed above, an increase in distribution generation would cause the risk of Model failure over a while. Some utilities may allow a trade-off to facilitate more DER for an occasional protection failure as a compromise. In those case, it could increase the probability of concept failure of the protection. It has to be understood that the customers will not be satisfied in either case as both would result in interruptions of power supply. A few possible causes of protection failures are discussed here,

- As shown in Fig. 11 [13], in a parallel feeders case, a fault, on the feeder with no generation could result in tripping of other feeder's upstream breaker (CB1) due to in feed from the generator. As explained in the earlier case, this could be more intense if the generation is synchronous. If the connected generator is connected through a Δ -Y with Y connection to the grid and grounded start point. This would create a low impedance path for zero sequence currents resulting in maloperation of the earth fault relay of the feeder.

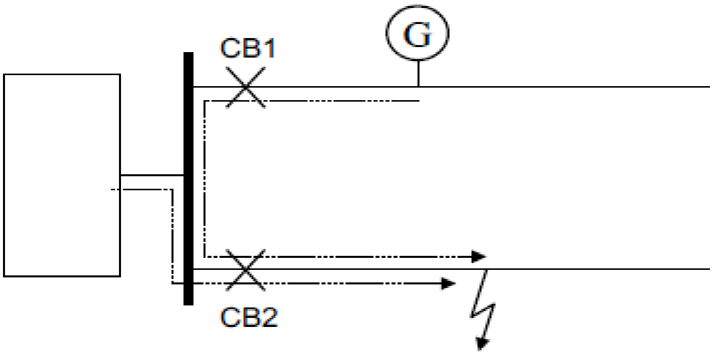


Fig. 11. Fault contribution from generator on a parallel feeder [13]

- When a generator is connected to a lengthy feeder in a radial feeding system, it would result in reduced fault currents at the start of the feeder. For a fault at the end of the feeder, the fault current sensed by the relay at the start of the feeder would be less than the overcurrent relay setting, this might even fail the operation of the relay. This is a major concern if the connected generation is a synchronous machine, as the fault current is higher. And this problem would be more dreadful for long feeders, as the fault current is already low due to high impedance. If the fault impedance is high, the condition will deteriorate even more. In simple terms, the lower the fault current setting, the higher the chances of failure to operate due to generation on the feeder. If the overcurrent relay setting is set as inverse time characteristics, these conditions would result in higher operating times.
- In this picture Fig. 12 [13] here, a low impedance fault after the generator is considered and as it can be seen, the fault current through CB1 would less than the case when there is no generation, this would result in either mal-trip or no-trip of protection depending on the location of the fault and over current settings at CB1.

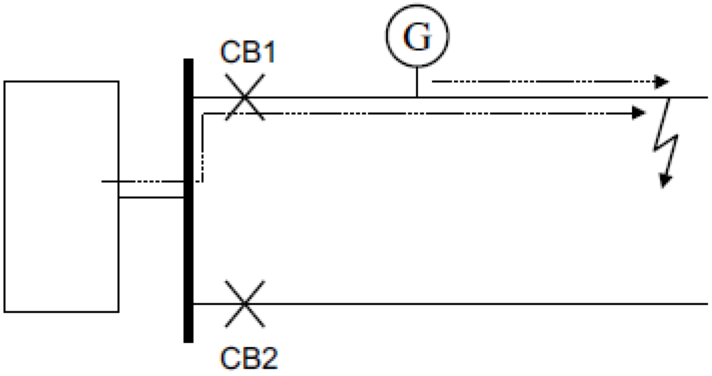


Fig. 12. Fault contribution from generator for a downstream faults [13]

- For a power electronic-based DER like solar power, the current contributions for faults may not be big enough for the overcurrent relay to sense, which would fail to operate. when there are multiple of these generations connected to a feeder, a fail to isolate during faults could results in serious damage to the equipment.

- When fuse saving is implemented, i.e., using a recloser to save fuse in case of transient faults, which would be cleared by reclosers with a simple reclosing function. These fuses are selected in a way that they will not be affected by the fault current during the first reclosing operation of the recloser. This coordination would be affected if there is a DER connected on the feeder because the design basis for this coordination considers the same through fault current for both fuse and reclosers. To make it more understandable, please refer to the following Fig. 13 [13]. For a fault that is downstream of the fuse, the DER would feed the fault current in addition to the current seen by the recloser. So, the fuse will act faster than the recloser compromising the coordination of the operation between them. This would eventually result in supply interruptions for downstream customers as the fuse has to be replaced by utility manually.

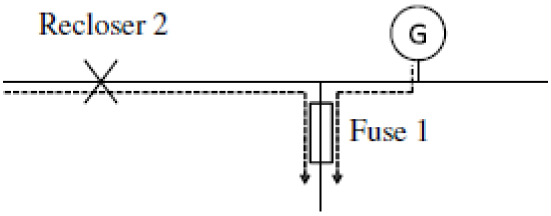


Fig. 13. Fault contribution from generator with fuse and recloser case [13]

- Referring to the earlier explanation, if two fuses are in series that are designed to operate in coordination with different time of operation. The existence of DER on the feeder would not only break this coordination but could also result in faster ageing of the upstream fuse. This is because fuses are coordinated by minimum melting time and maximum clearing time. When the time of operation exceeds the minimum melting time but lower than the maximum clearing time, the fuse will not break but age faster.
- If the distribution system is a ring/loop model, which is quite common in many utilities due to the reliability of the system. The protection coordination uses overcurrent in combination with directional overcurrent relays. Due to parallel fault loops, the coordination settings in this system would be challenging even when there is no generation is connected and the presence of the DER would complicate it further.
- Many utility companies use fault indicators to localize the fault. And usually, the fault data is recorded mostly at selected points of the network due to the cost involvement of the equipment. And a DER presence in the system would result in mislocation of the faults as the current contribution from the consumer’s generation is mostly not considered. A more stringent and effective system would be required which would result in excess investment in equipment.

These are a few of the many cases that could be noticed in the distribution system with DER connected. The downside of this arrangement is most of the DER that are being encouraged by the electricity markets are renewable energy resources. As we know, an uncontrollable input to RES results in a variable output. So, the fault current contributions would vary widely and would make it more challenging to protection engineers and network operators. These problems can be addressed with an Adaptive protection novel approach which would be discussed in detail further.[21]

3. Adaptive Protection

Adaptive protection is a concept that has been around for many years and is being studied extensively, it is one of the best solutions to solve protection problems in smart grids due to influence from DERs. The key idea behind this principle is to continuously adjust the relay settings of IEDs in response to changes in network state. Changes such as, whenever the DER starts generation or a major area of the network is isolated etc., and the relay settings are re-calculated and being updated in the relays via smart grid communication features to relays. However, if there is a fault, the relay will still make decisions based on the current relay settings available in it. The main advantage of this approach is that the relay settings are not required to cover every operation conditions of the network and thereby increasing the selectivity.[22, 23]

There have been several approaches and methods suggested to incorporate adaptive protection in smart grid systems. However, such new approaches which have not fully tested or have not formulated in grid codes would pose the element of risk, since the protection is crucial for the safety of the equipment and operators, it may not be considered by many. In addition, the integration of such systems is also a costly matter for many utilities. As a result, a quick and cost-effective solution that requires less implementation and makes effective use of existing infrastructure is needed. Smart grids are based on a robust and efficient communication backbone structure, and utilities from various areas can use relays from various manufacturers (OEMs), so the proposed technology must effectively use these existing facilities and provide a reliable solution. One such scheme is being discussed here with the details of architecture implementations.[24]

3.1 Functional and user requirements

Similar to conventional protection system life cycle, which includes design, development, installation, testing and commissioning. Adaptive protection would follow the same. However, different users/utilities may have different design requirements as per their grid code or system topology. So, a common design requirement will be agreed upon among users and the developers/suppliers (OEM). A detailed study with multiple operational cases should be carried out during the design stage. And these details are to be used to develop scheme logic and to calculate relay settings for relays at different points in the network. The approved scheme would be installed at the site and will be tested and commissioned to validate electrical connection and protection functionality. During operation, all data files logged to monitor the performance of the system any error in the operation would be notified and to be studied in detail. If there are any changes to the primary system, the details are to be updated to create new relay settings.

3.1.1 Functional requirements

To achieve a suitable relay setting as per the changes in primary and to deliver better performance, four main functions are proposed in this scheme, and they are “power system event detection and qualification, post-event evaluation of protection performance and post-event setting calculation and application”.

A simplified functional flow of the proposed ADP (Adaptive Protection) is shown in Fig. 14 [25]

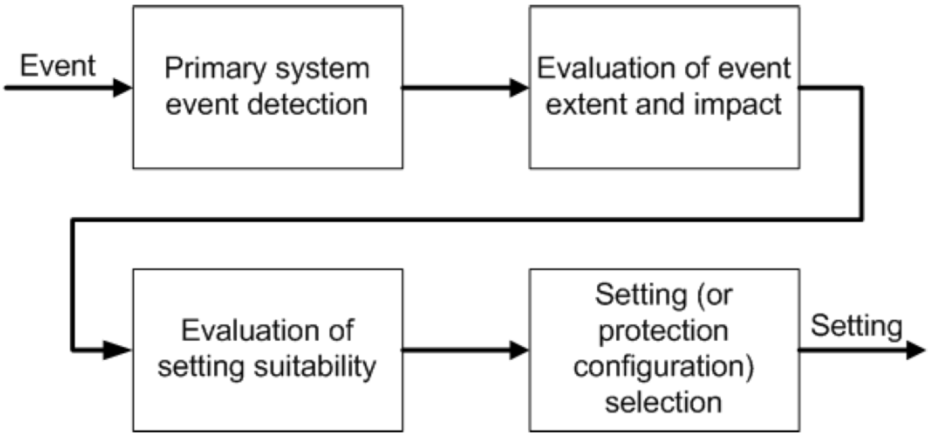


Fig. 14. Adaptive protection scheme operation [25]

- In event detection, using measurements available locally or remotely through a communication channel, the negative impact of power system events are detected. And by using defined set parameters, these events qualification is evaluated. The time interval in extracting information of the events is to be defined during the designing of the ADP scheme.
- Performance of protection system post-event is essential in deciding the validation of the applied settings. The easiest way to do that is by evaluating the network for each possible case during the design process and using that reference data in this function block because performing these calculations in real-time would be very process consuming.
- If the result of the earlier functional block is unsatisfactory, the pre-calculated settings that match with the corresponding event will be made available as the original settings. This process is to be tagged and observed as this should not result in the tripping operation of the existing relays.[25]

3.1.2 User requirements

The designed Adaptive protection must adhere to these user requirements to deliver an effective solution, and these should be measurable enough to validate the scheme developments at different stages. The requirements are explained in detail here.[25]

- The core principle of an adaptive protection scheme is to alter the existing relay settings and configurations. So, the proposed scheme should utilize the existing available protection functions in the utility and applying the ADA scheme should improve the selectivity and performance of the system.
- Since it is difficult to provide a common ADA functionality for all kind of possible events, the users must know and define the events that should activate the ADA scheme. They are expected to have a clear understanding and provide this data during the design stages. Any further changes in topology thereafter are to be studied in detail.
- The proposed scheme should be simple to integrate with current brownfield sites and networks. OEMs should make use of existing assets and should propose a minimum number of new equipment to facilitate the scheme.
- The overall performance of the protection scheme is expected to improve from any existing system shortfalls. In addition, the failure of ADA should not interfere with the existing protection functionality of the network.

- In addition to the incidents and disturbance reports, all signals that are part of the ADA scheme are required to be tracked and logged. This information and models that are part of schemes should support industrial standards to provide interoperability.

An architecture of adaptive protection system is discussed here with aims to handle the requirements of users as well as functions that are discussed earlier.

3.2 Adaptive protection architecture

The adaptive protection architecture (APA) resembles the smart grid architecture. Here, in Fig. 15 [25] the architecture of the smart grid and the architecture of APA are both are shown for understanding purposes. The proposed architecture has three characteristic layers, namely, execution layer, communication layer, management layer. The layer's scope is influenced by the extent of the information exchange among the layers required.

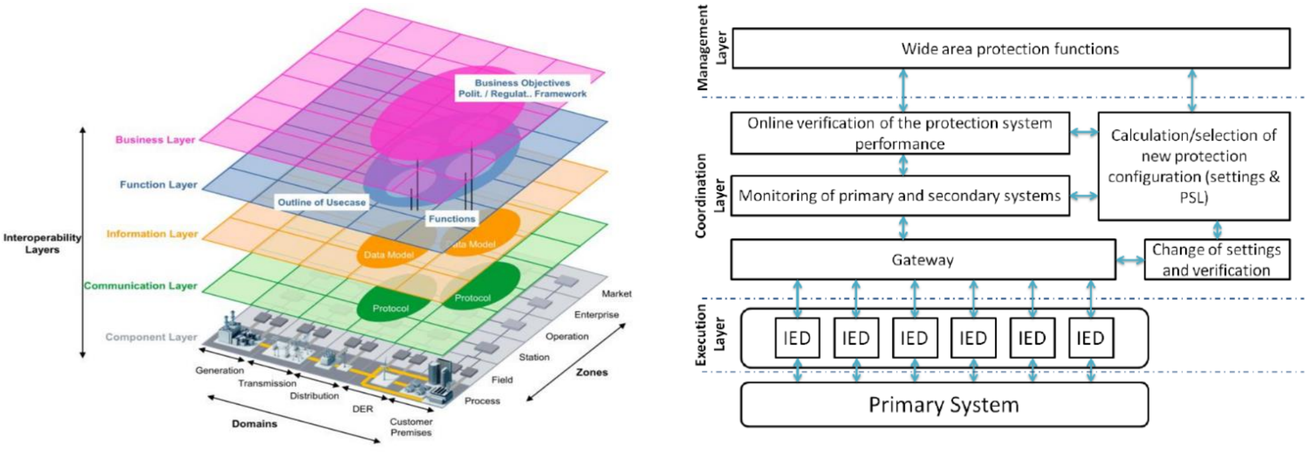


Fig. 15. Comparison of smart grid and adaptive protection architectures [25]

- *The execution layer* represents all the IEDs that are directly interacting with the primary system. All the status signal, measurement of voltage and currents that are required for the scheme (as defined during design stages) are being communicated to the coordination layer. These same parameters are being used by the IEDs at this layer to execute conventional protection functions. Since it is responsible for the execution of protection operations, so is the named Execution layer.
- The *coordination layer* functionality is determined by the scheme related status information of the equipment in the primary network. The received information on status and measurements will be analyzed here for the protection evaluation to identify the thresholds with pre-defined events. If the received information sets off triggers, new settings are to be implemented and will be communicated down to IED's in the execution layer. So, the accuracy and performance of this layer depend on the information received from the execution layer. However, the response time of the coordination layer can be in the order of seconds as it involves computations of a wide network.
- The *management layer* is the bridge between the protective functions in the execution layer and the main control room. The advanced protection functions in control rooms are slow and

rely on the data from phaser measurement units to understand the state of the system. The equipment in this layer would be overviewing the performance of protection functionality in several other zones. This is necessary for maintaining the stability of the power system.

The functionality of each layer described here is very crucial for the consistent operation of Adaptive Protection. However, the nature of the network and type of the protection schemes involved would heavily influence the functionalities of the layers.[26]

3.3 Implementation of Adaptive protection

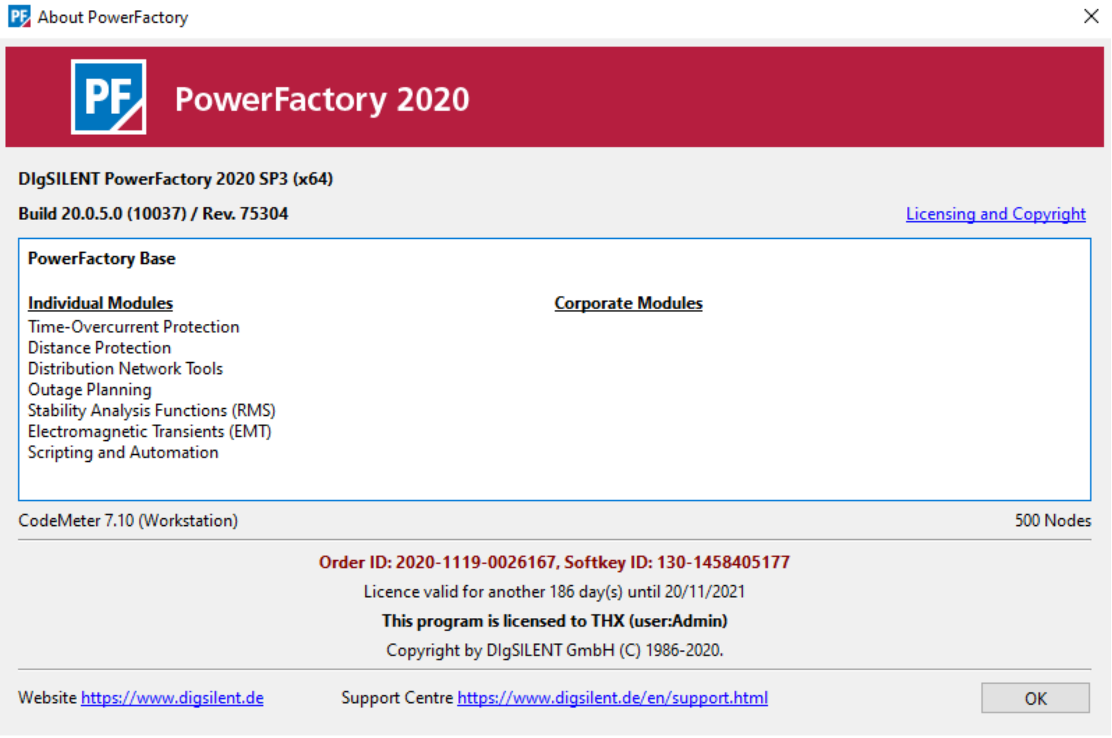
3.3.1 Simulation software requirements

Increasing demand for power results in larger and complex electrical power systems, analysing these networks for power flow, short-circuit and other related studies is a complex task. Load flow problem with numerical methods needs several calculations depending on the number of buses in the network. It is a common practice to use electrical simulation software for more accurate calculations and result in analysis. There are various simulation software options available on the market, with the most well-known and notable ones being Powerfactory from DIgSILENT (Germany), ETAP (USA), PSSE (Germany). However, Powerfactory is preferred above others due to their complete support for API-based software control using Python and the significant number of built-in programming objects. Furthermore, their assistance to students with thesis-based research is another reason to select Powerfactory software for this project.

“DIgSILENT” is an acronym for “DIgital SImuLation of Electrical NeTworks”, Powerfactory from DIgSILENT is a computer-aided engineering program for analysing transmission, distribution, and industrial electrical power networks. It has been built as a sophisticated integrated and interactive software package dedicated to the electrical power system and control analysis to meet the primary goals of planning and operation optimization.[27] Powerfactory was created as an integrated engineering tool that offers a comprehensive range of power system analysis features in a single executable software. Among several features it supports some of the key aspects are:

- Powerfactory fundamental functions include project structure, study case definition, modification, and organization. As well as basic power system studies such as load flow studies with numerical algorithms, short circuit studies, relay coordination, network management, data management, results, and reporting. These features are part of the basic package of the software.
- Advanced features are divided into several packages to provide flexibility for the user to select based on the requirements. Some of those packages are, Protection functions, Cable analysis, Distribution network tools, Stability analysis (RMS), EMT analysis, Scripting and automation, etc. [28]

As the current project requires to simulate, analyse the distribution system. In addition to Powerfactory’s basic package following advanced features are requested from the DIgSILENT to activate in software and the license is enabled for 500 active nodes, refer to Fig. 16 for more details.



DIgSILENT PowerFactory 2020 SP3 (x64)
Build 20.0.5.0 (10037) / Rev. 75304

PowerFactory Base

Individual Modules
Time-Overcurrent Protection
Distance Protection
Distribution Network Tools
Outage Planning
Stability Analysis Functions (RMS)
Electromagnetic Transients (EMT)
Scripting and Automation

Corporate Modules

CodeMeter 7.10 (Workstation) 500 Nodes

Order ID: 2020-1119-0026167, Softkey ID: 130-1458405177
Licence valid for another 186 day(s) until 20/11/2021
This program is licensed to THX (user:Admin)
Copyright by DIgSILENT GmbH (C) 1986-2020.

Website https://www.digsilent.de Support Centre https://www.digsilent.de/en/support.html

Fig. 16. License and module details of Powerfactory software used

- Time-Overcurrent Protection
- Distance Protection
- Distribution Network Tools
- Outage Planning
- Stability Analysis Functions (RMS)
- Electromagnetic Transients (EMT)
- Scripting and Automation

3.3.2 Adaptive Protection with Powerfactory

The functional requirements of the Adaptive protection system give a clear understanding that this scheme can be implemented on an existing network. However, for the research application, where accessing a live network with several protection devices is difficult. The APA scheme in [25] requires a different set-up with a Hardware-In-Loop and working relays from different manufacturers, and sourcing these for current research work are considered to be challenging. Because of this an alternative approach is investigated in alternative ways, such as implementing the network and working with scripting feature is evaluated as a part of this project. With the help of the *Application Programming Interface* (API) feature of Powerfactory from DIgSILENT GmbH, is used.

In power system studies, it is normal to simulate a base scenario and several variants of the base scenario as special cases. Many software has options to create study cases and operation scenarios for creating special cases to study system behaviour. However, many few can automate to perform multiple calculations without intervening in between. Powerfactory from DIgSILENT is one such software that has a built-in scripting language called DSL (DIgSILENT Scripting Language) for automation purposes.

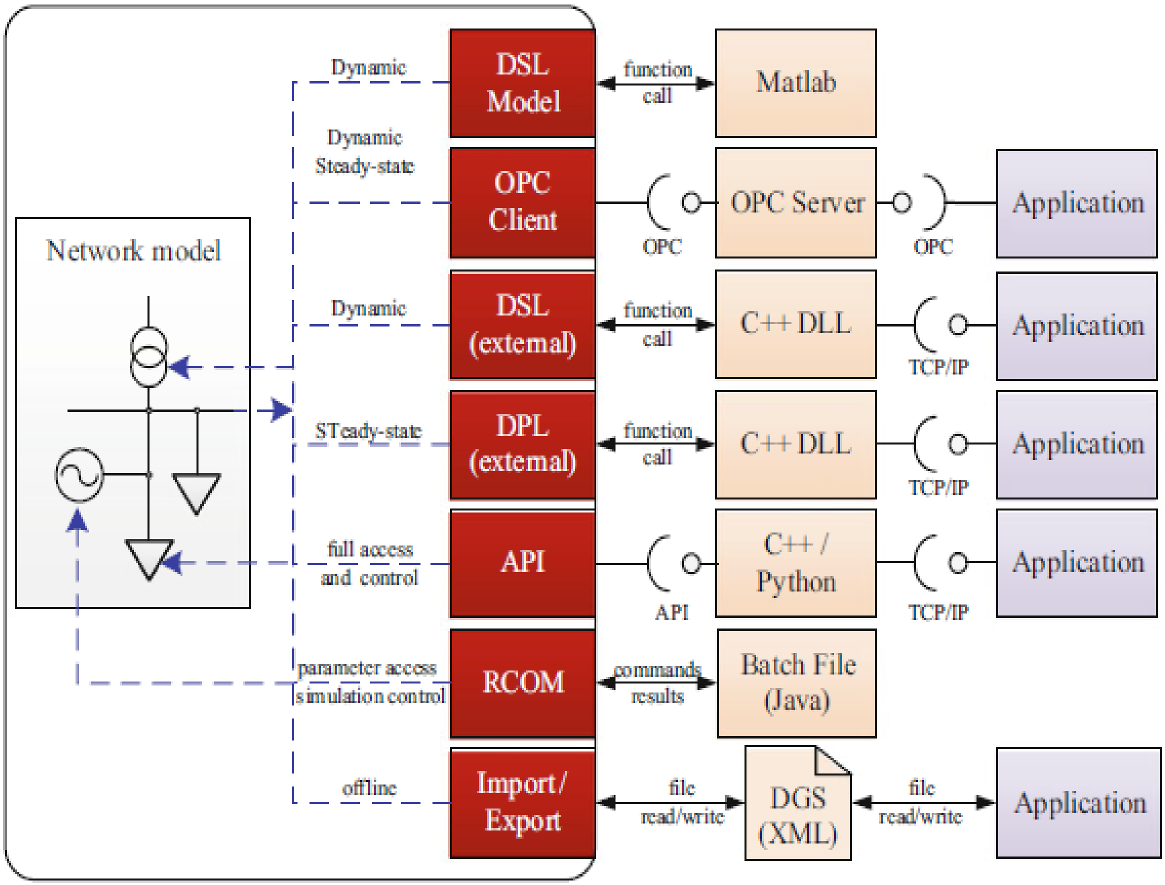


Fig. 17 Scheme of python integration with Powerfactory. [30]

In addition to this, Powerfactory also supports co-simulation [29] from third-party simulation software such as C++, MATLAB, OPC and Python etc. Each of these software has its advantages and limitations in controlling the network in Powerfactory. Among all, C++/python are the only programming languages with API support to communicate with Powerfactory, ref to Fig. 17 [30] for more detailed representation. Due to the advancement and availability of a wide range of libraries python is favoured over C++ for this research work.

As shown in Fig. 17 [30], DIgSILENT Powerfactory's Application Programming Interface (API) offers a python compiler to access Powerfactory's functionality into their program. API offers direct access to Powerfactory's data models, varied calculations, and results. Since the API is intended to be an automation interface, it precludes a thorough understanding of the Powerfactory data model and how to manage various tasks manually, as well as an understanding of the participating objects and commands.

Before implementing the APA scheme, it is very important to have a functional distribution system simulated in software. After successful evaluation of network data and simulation, the simulated network has to be studied for load flow studies. If the voltages of the buses are satisfied, the topology of the network will be validated for a radiality check. Since the relays considered in this network are for non-directional type and it is important not to have any ring structures in the network as it could complicate the study.

A successful network with satisfied load flow results will be studied for SC study and fault currents will be calculated for each bus to calculate the sizing of the current transformer and to set the values of relay settings. The connected relays will be coordinated properly using IDMT coordination and validate for faults across the network.

To generate cases of protection failures, a DER energy source will be connected at weak short circuit level buses and the relay coordination will be checked. When the relay settings are observed to fail, an alternative relay will be created at the said bus with revised settings with the DER in the network.

Adaptive protection algorithm will be formulated in a way that when DER is activated in the system, it will activate the relay with revised settings and earlier settings will be disabled. This algorithm will be written in python scripting and validated for faults to check its operation.

4. Project Description

To understand and study the need for ADP architecture for this project, an existing utility system is simulated in Powerfactory software. The network data that is being used for this implementation is from the ’VIDZGIRIO (Alytus) substation network’. Due to the limitation of the number of nodes for the license of software, only a part of the network is implemented and studied further.

The entire project is divided into 3 major subcategories,

- Network building, and Load flow validation
- SC study and Relay coordination.
- DER integration, ADP implementation using Python API and results analysis.

Tasks, as well as the outcome for each stage of the project, are explained hereunder.

4.1 Network building and Load flow validation

4.1.1 Network building

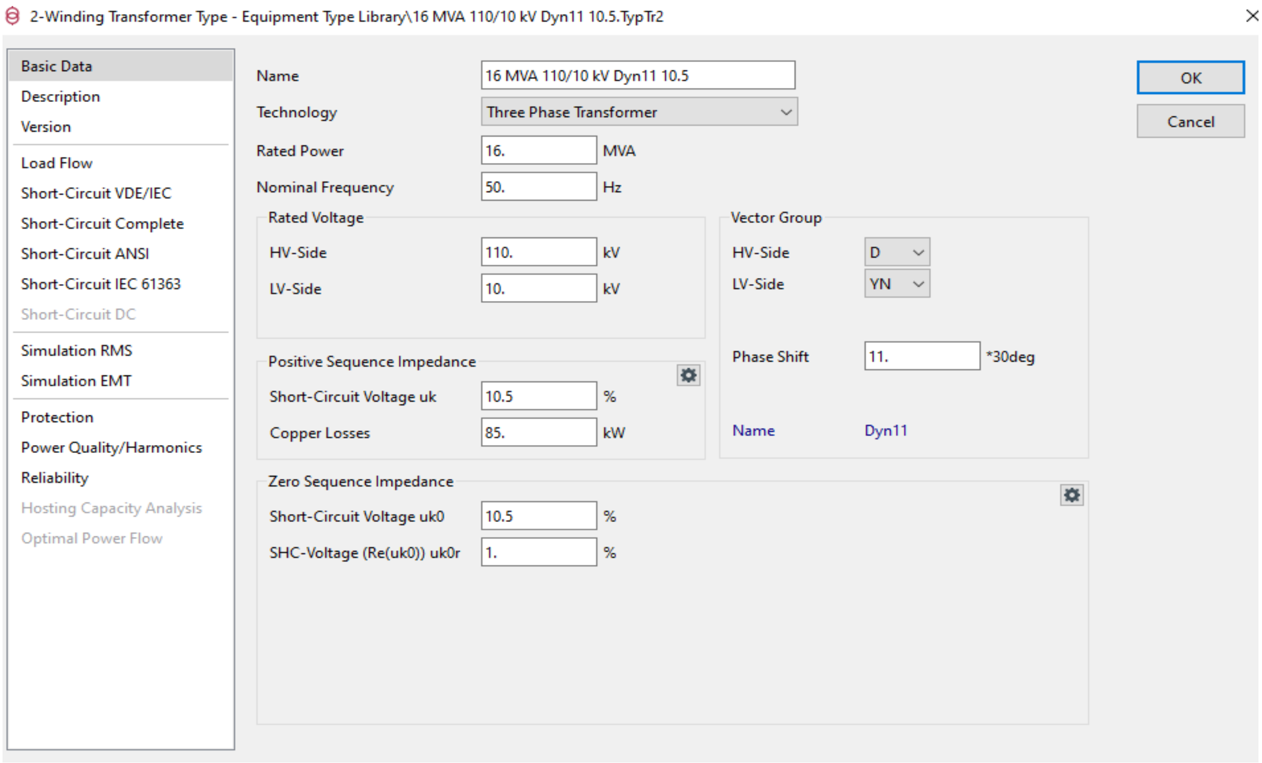
To perform a power system simulation in any computer-aided simulation software, network model building is the primary step. The accuracy of the simulation results depends on the authenticity of the equipment data in the model. Powerfactory supports uses a hierarchical, object-oriented database. The graphical user interface of Powerfactory allows to draw network as drag & drop, data is entered by first designing network elements, then altering and assigning data to these objects.

Any significant power network has a different kind of electrical equipment connected based on the application and the following are the ones used in this project and the configuration of these in Powerfactory will be discussed here in detail.

- External Grid
- Transformer
- Busbar
- Circuit breaker
- Cable (or transmission line)
- Load
- Current transformer
- Relays

For equipment to connect inside a network, it is necessary to create an object type in the library first. This can be done two ways, either by copying a similar object from the global library or by creating a new object in the project library. Objects in the Powerfactory library holds the major type of data of the element. Before create/edit an element type data in a model, the project and relevant study case are to be activated and by navigating to the library section of the project in the data manager, all the available type objects in the project can be accessed.

For a 2- winding transformer type object, the type data to be entered is shown in Fig. 18. In the basic data page, rating, winding configuration, voltage levels, frequency as well as impedance data of the type of transformer under use will be entered. This data can be extracted either from test reports of GTP of transformer or nameplate of the transformer.


2-Winding Transformer Type - Equipment Type Library\16 MVA 110/10 kV Dyn11 10.5.TypTr2

Name: 16 MVA 110/10 kV Dyn11 10.5
Technology: Three Phase Transformer
Rated Power: 16. MVA
Nominal Frequency: 50. Hz

Rated Voltage
HV-Side: 110. kV
LV-Side: 10. kV

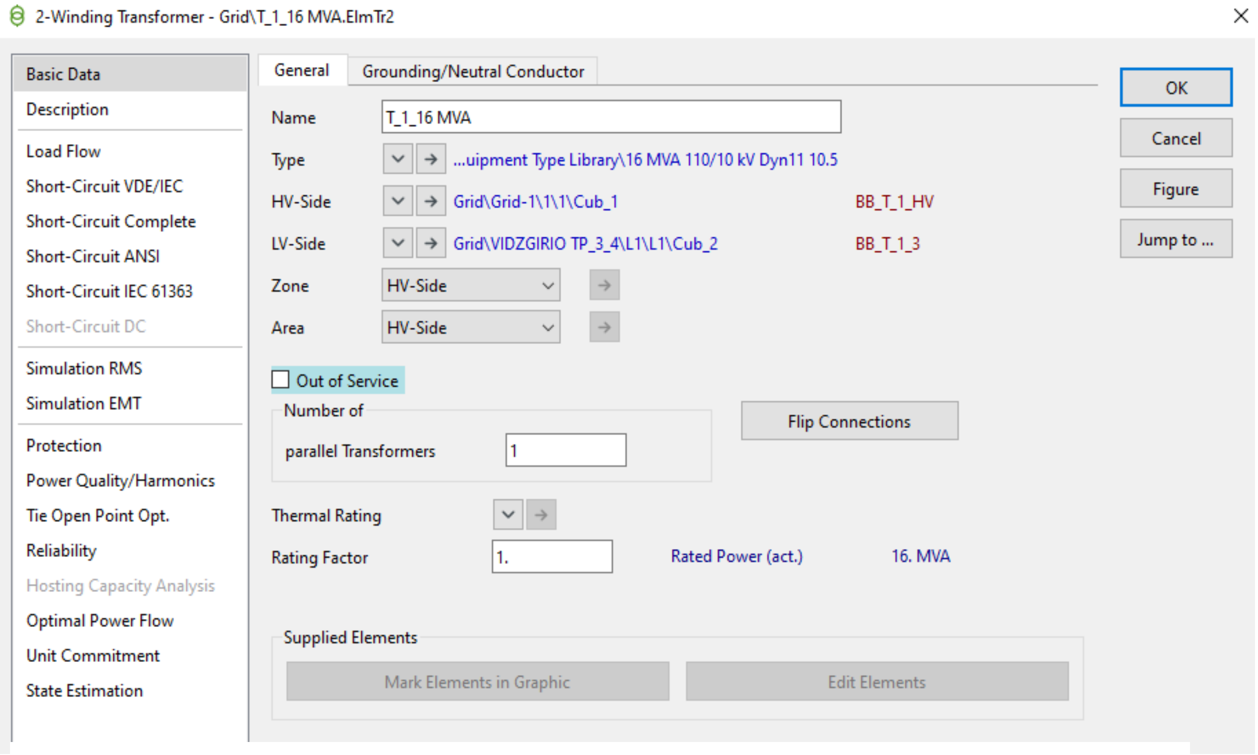
Vector Group
HV-Side: D
LV-Side: YN
Phase Shift: 11. *30deg
Name: Dyn11

Positive Sequence Impedance
Short-Circuit Voltage uk: 10.5 %
Copper Losses: 85. kW

Zero Sequence Impedance
Short-Circuit Voltage uk0: 10.5 %
SHC-Voltage (Re(uk0)) uk0r: 1. %

Fig. 19. 2-Winding Transformer equipment type data configuration page from library

In addition to this basic data, study-related data is categorized separately, and it can be observed in Fig. 18. Load Flow data has options to configure tap changer, magnetizing impedance etc. whereas short-circuit data is specific to the type of short circuit underuse and for transformer, it is the same tap changer data since tap changer position varies impedance of the transformer.


2-Winding Transformer - Grid\T_1_16 MVA.ElmTr2

General | Grounding/Neutral Conductor

Name: T_1_16 MVA
Type: ...uipment Type Library\16 MVA 110/10 kV Dyn11 10.5
HV-Side: Grid\Grid-1\1\1\Cub_1 BB_T_1_HV
LV-Side: Grid\VIDZGIRIO TP_3_4\L1\L1\Cub_2 BB_T_1_3
Zone: HV-Side
Area: HV-Side
☐ Out of Service
Number of parallel Transformers: 1
Thermal Rating
Rating Factor: 1.
Rated Power (act.) 16. MVA

Fig. 18. 2-Winding Transformer data configuration page in model

Here Fig. 19 shows how the configuration page of a transformer in software would look like. HV and LV side details are automatically updated when a transformer is connected between two busbars or cubicles. Other important parameters to configure here are the name, which can be a transformer ID in the network or serial number or any unique identifier. The thermal rating factor in configuration allows the limit to overload and it will be used to calculate % of loading during load flow calculations. The type of grounding connection is defined in basic data as well. In the load flow page of the element data here, the current tap position of the transformer will be updated, in addition to that any external control of tap changers can be configured here.

Creating a Bus bar in Powerfactory is easy as it can be, with just a drag of a button, a bus configuration from a single bus bar to a standalone substation with bay elements can be created in the model. As explained in the case of transformer configuration earlier, before creating any busbar (or substation) in the network, it is necessary to create or import a relevant type object to the library. All elements created in the substation are configurable.

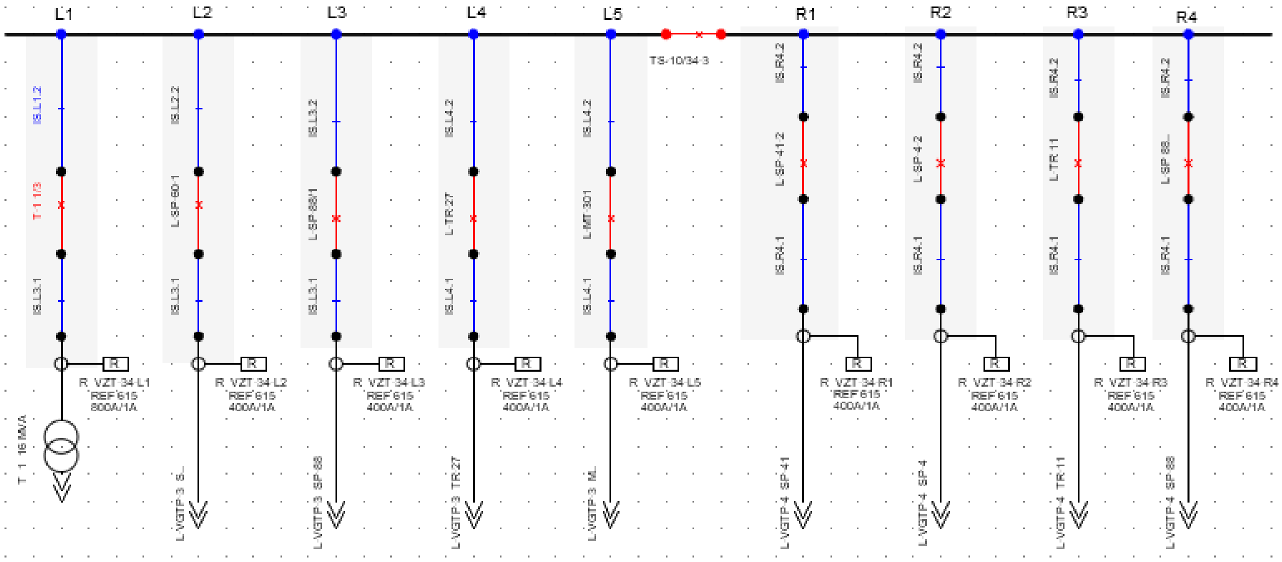


Fig. 20. A substation with a single busbar with Tie switch model

As shown here in Fig. 20, a substation with a single busbar and tie switch model can be observed. Each bay is named by software concerning the side of the Tie switch, L is for left and R for right. The numbering sequence is from left to right, which explains the number for each bay in Fig. 20. Any typical bay in this model has 3 basic elements, 2 isolator (or disconnectors) separating busbar – CB and cable/transformer – CB. This configuration is used to replicate the practical isolation practice of disconnectors in air-insulated switchgear systems. And each bay is added with a current transformer and relay for protection-related applications.

In addition to a busbar element, Powerfactory offers a cubicle option, which is physically the same as a switchboard. And inside cubicles, there is a provision to add circuit breakers, relays, instrument transformers and other elements. This feature of Powerfactory gives great flexibility in designing an organized model with fewer elements visible over the model. So, an entire bay in Fig. 20 can be shown as a small square in SLD, this option of configuration is widely used with a distributed transformer, cables, and DER connections.

A substation shown in Fig. 20 is shown as a straight line in overall Grid SLD, which can be seen in Fig. 21 here. However, some small substations are shown as circle or rectangles with the green background here symbolizes the secondary substations. In this model part of the distributed network is configured inside these secondary substations for better organization of network and data.

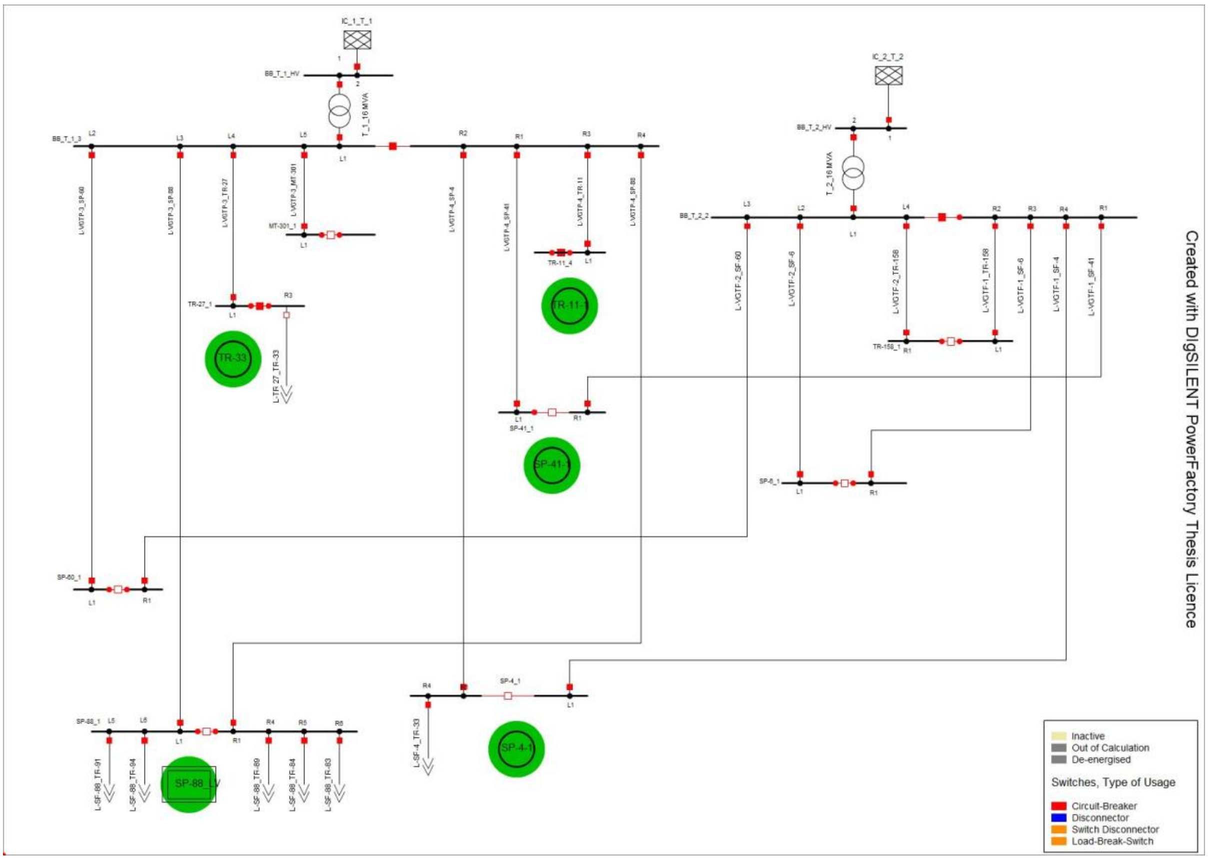


Fig. 21. Complete SLD of the model from Powerfactory software

A circuit breaker is the most important element in a power system as it gives the utility company flexibility of changing network topology according to the requirements. However, due to the cost of the circuit breakers, it is not always practical to use CB in every part of the network. To replicate the same in model, in the least significant areas of the network, circuit breakers are replaced with disconnectors, one such major element is the cable, all cables connecting different part of the network are connected through a circuit breaker and disconnector combination. Only the cables connecting between substations are excluded as the breakers between them to be time coordinated.

There are 3 different types of circuit breakers used in the entire model, each for a different type of voltage level that they are connected to. The SC capacity of breakers is selected as equivalent to the busbar capacity since the sizing of the equipment is not the priority of this project. The timing of the breaker operation is selected appropriately on the library configuration page.

Similar to the configuration of a circuit breaker, a separate object for a 10 kV disconnector is created in the library to use at a different part of the network for cables. The colouring layer for the disconnector can be selected in layer options of the model, to differentiate them circuit breaker locations in the network.

Powerfactory global library comes with a wide variety of cable types from different manufacturers. If the cable under used in the network is available in the project library, the same object can be imported into the project library and can be used. If a new type of cable is to be created from the template, then it is very essential to have all relevant data of the cables in use. In this project as gathering the exact data is highly complicated, pre-defined type objects from the global library are used based on the size of the cable connected in the network.

It is quite common to have different cable sizes connected together in distribution system. This could be either the result of miscommunication between the operation team and the planning team or the need-based act of the maintenance team. In either case, in cases where different cable sizes are observed to connected in series, the cable with the smallest size is preferred for the analysis purposes. This is decided, as a reason if the calculations and studies are satisfactory for the smallest size, they will be acceptable for the entire feeder.

Loads in distribution system can be vaguely classified as domestic, commercial, and industrial. Collecting load data connected to every distribution transformer is an impossible task as the load can be very variable and no utility has control over it, not to mention the number of transformers connected in the network. The load connected in Powerfactory for this project is lumped. As all loads cannot be of the same rating, an element of variation is introduced. Loads are categorized into types based on the rating of the transformer. Calculated as a percentage of rating of the transformer and power factor is maintained above 0.9 to avoid the usage of capacitor banks in the network.

A major assumption made for this project from the usual distribution practices is that all LT side of the transformers is connected with LVCB in provision with a numerical relay. This is to have greater flexibility in the relay coordination study, which will be discussed in greater detail in the following sections of this work.

Each protective part of the network is configured with a current transformer and the working principle of the current transformer is discussed in earlier sections of this work. From the formula of ALF, it can be seen that the ratio of the transformer can be designed according to the SC availability at the connection point and the secondary equipment connected to the current transformer. To explain the sizing consideration of the CTs used in the network, one example calculation for the 1000 kVA Transformer's HV side is detailed here.

Transformer rating - 1000 kVA

Voltage on HV side - 10 kV

FLA on HV side - 57.80 A

Rated I_{th} of CT - 69.36 A (1.2 x FLA)

SC current (from study) - 8901 A (highest for HT busbar in the network)

SC current for 1s - 15417 A ($\sqrt{3}$ times of SC current for 3 secs)

IEC rated SC current - 16000 A (closest value is selected)

Relay input impedance - 100 mΩ

Conductor resistance at 20°C - 4.61 mΩ/m (for a 2C x 4 mm2)

Temperature co-efficient (α) - 0.00393 1/K

Conductor resistance - 4.61(1+0.00393(75-20))

= 5.61 mΩ/m (corrected to 75°C)

Loop resistance of cable - 2*100*5.61 = 1.122 Ω (100 mtr assumed)

Total connected Burden - $I_s^2 * (R_r + R_l)$

$= 1^2 * (0.1+1.122) = 1.222$ VA

CT burden considered - 10 VA (atleast 5 times the connected burden)

ALF considered - 20.

Resistance of the CT (from burden) - 5 Ω (most common resistance selected)

Corrected ALF value (ref IEC) - Rated ALF x $\frac{S_r + (I_2^2 * R_{ct})}{S_c + (I_2^2 * R_{ct})}$

$= 20 * \frac{(10 + 5 * 1^2)}{(1.222 + 5 * 1^2)}$

= 48.

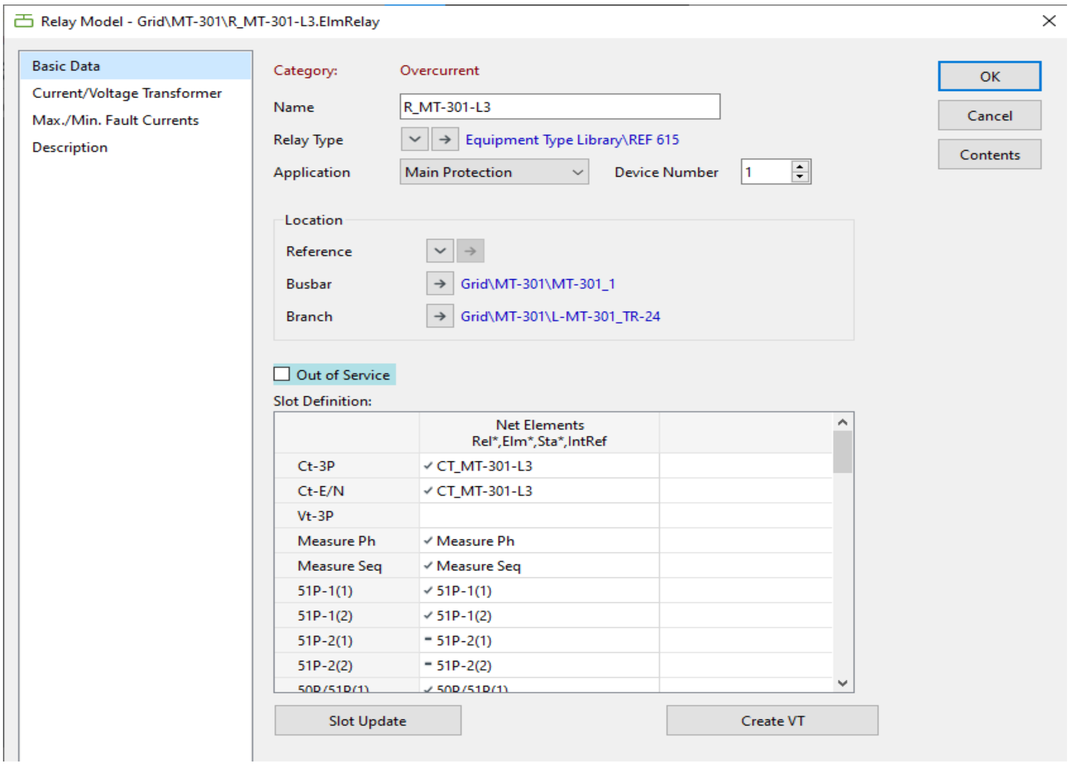
Required ALF - 16000 (SC rating) /400 (CTR)

= 40.

Since the corrected ALF is greater than the required ALF, the calculated CT of 400/1A, 5P20, 10 VA is appropriate to use for the HV side of the transformer for 1000 kVA transformer. Using a similar procedure, the sizing for the remaining transformer's HV and LV sides were calculated.

Every circuit breaker in the network is connected with a dedicated relay connected to it and acts as a protection device. Since the object of this project is to investigate the coordination issues that arise with overcurrent relays, a feeder protection relay REF 615 from ABB is used. This one of the commonly used numerical relay in both distribution as well as industrial systems. The major advantage of this relay is that it supports various kinds of current and voltage-based protection and configuring this in the network would give the flexibility to create studies in future. For this project, only overcurrent elements are kept active by keeping others in a deactivated state.

The configuration page for the REF relay is shown in Fig. 22 here, most of the configuration is done on the basic data page. In this project only, one relays are used for protection, relays are configured as main protection. By using the 'Solt update' option of the basic page, the CT details to the relay can be updated. If the relay is configured inside a cubicle where CT and breaker are configured as well, Powerfactory will automatically assign relay inputs to CT and relay outputs to the circuit breaker.



Relay Model - Grid\MT-301\R_MT-301-L3.ElmRelay

Category: Overcurrent

Name: R_MT-301-L3

Relay Type: Equipment Type Library\REF 615

Application: Main Protection

Device Number: 1

Location

Reference:

Busbar: Grid\MT-301\MT-301_1

Branch: Grid\MT-301\L-MT-301_TR-24

☐ Out of Service

Slot Definition:

	Net Elements Rel*,Elm*,Sta*,IntRef
Ct-3P	✓ CT_MT-301-L3
Ct-E/N	✓ CT_MT-301-L3
Vt-3P	
Measure Ph	✓ Measure Ph
Measure Seq	✓ Measure Seq
51P-1(1)	✓ 51P-1(1)
51P-1(2)	✓ 51P-1(2)
51P-2(1)	- 51P-2(1)
51P-2(2)	- 51P-2(2)
50P/51P(1)	✓ 50P/51P(1)

Fig. 22. Relay configuration page from Powerfactory software

Since there is no voltage transformer used in this network, the VT connection part of the relay configuration is observed to be empty here. The relay connection for the substations with bays configuration can be noticed in Fig. 20. Where the relay is manually connected to CT through the wire, even in this condition, the breaker details are automatically updated inside the relay.

Relay protection elements in a numerical relay are subjected to the manufacturer, however for the ease of understanding, Powerfactory refers to protection functionalities with ANSI numbers and to make a correlation among ANSI codes in relay configuration to the actual relay operation, Powerfactory has provided a reference document for every relay in their global library.

ANSI numbers with the '-' mark in Fig. 22 are the protection functions that are disabled inside the relay and they can be activated at any time. Calculation of the parameters for the relay operation will be discussed in relay coordination section of this work.

4.1.2 Load Flow Study

After successful modelling of the network, it is very essential to evaluate the voltage profiles, active and reactive power flow inside the network. This exercise will serve two major purposes. It would help to identify the problems associated with the element data configuration in the model and it would also give a clear understanding of voltage profiles based on the topology of the network.

Load flow equations are used to analyze power systems under non-failure steady-state conditions. Where steady state is characterized as a condition in which all variables and parameters are assumed to be constant throughout the evaluation period. A load flow equation specifies the voltage magnitude and angle of the nodes, as well as the active and reactive power flow on branches. The network nodes are usually defined by stating two of these four quantities. [27]

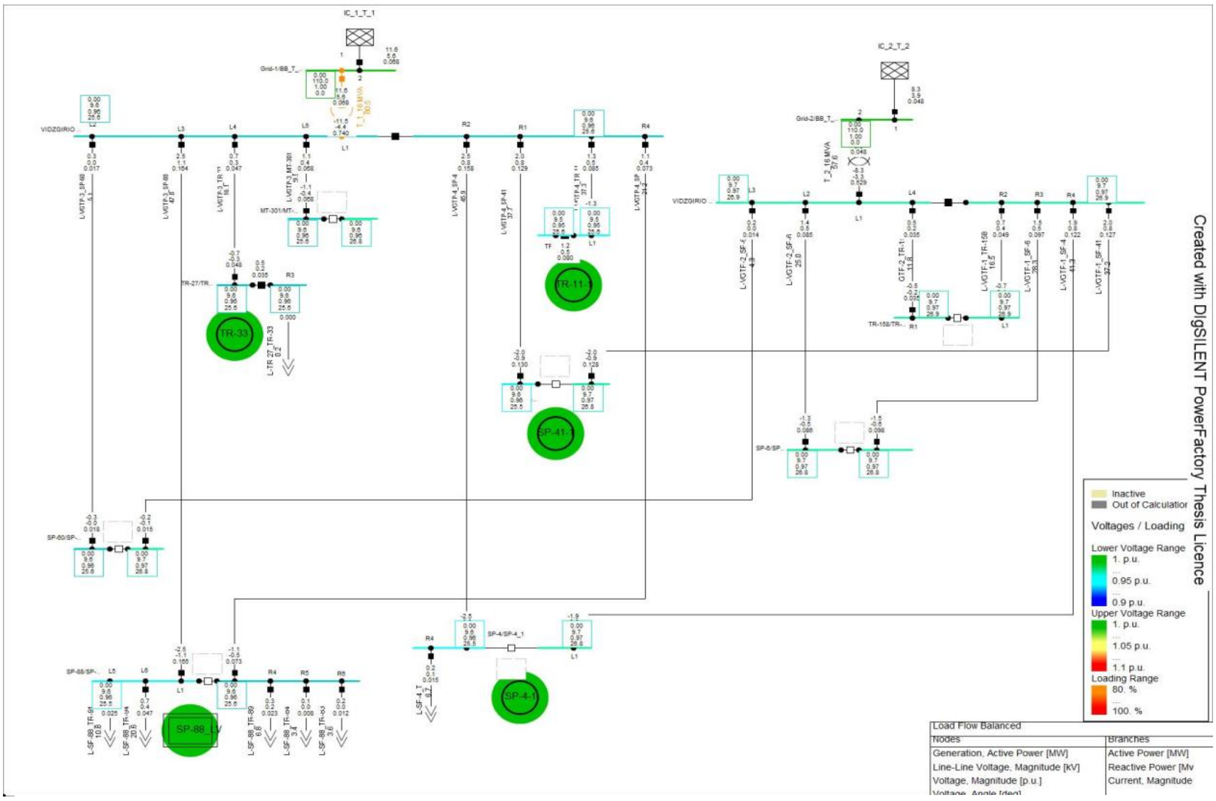


Fig. 24. Load flow results mapped on to SLD

By using the load flow study, the loading of cables, transformers are adjusted and tap settings of the transformers will be modified to match the voltage of the buses to within the allowed range. To solve

Fig. 23. Load flow results mapped on Feeder view of network

the load flow problem in Powerfactory, the classical Newton Raphson method using the power equation is used. And the network is considered as a balanced positive sequence in nature. After the solving, the results will be mapped onto SLD in the diagrams page and the same can be observed in Fig. 23 here. The colour-coded scale on the right side of the figure in Fig. 23 shows the voltage values of the buses per unit scale. Where yellow being marginally loaded and red being heavily loaded.

A complete view of the network can be created by using the ‘diagram layout tool’ option in the software and as shown in Fig. 24, as it can be noticeable here, the majority of the network is operating with healthy voltages and adequately loaded. Results of this analysis can be exported for further studying.

4.2 SC study and Relay co-ordination

4.2.1 Short Circuit study

Every power system is designed to handle adequate amounts of short-circuit currents in the system. However, the system is always built to avoid short circuits and always considered to be fault-free, but it is really impossible to influence every factor that would lead to a short circuit in the system. So, an alternative protection system is in place to protect the expensive equipment in the network from the short circuits.

To design a protection system for an equipment connected as a part of the network, it is very essential to calculate the current for different kinds of fault types. This information is very helpful to know the maximum expected currents to be expected and to correctly dimension the devices There are different standards for calculating short circuit currents without the use of load information and the most notable one is IEC 60909 method, in which maximum and minimum short circuit currents are

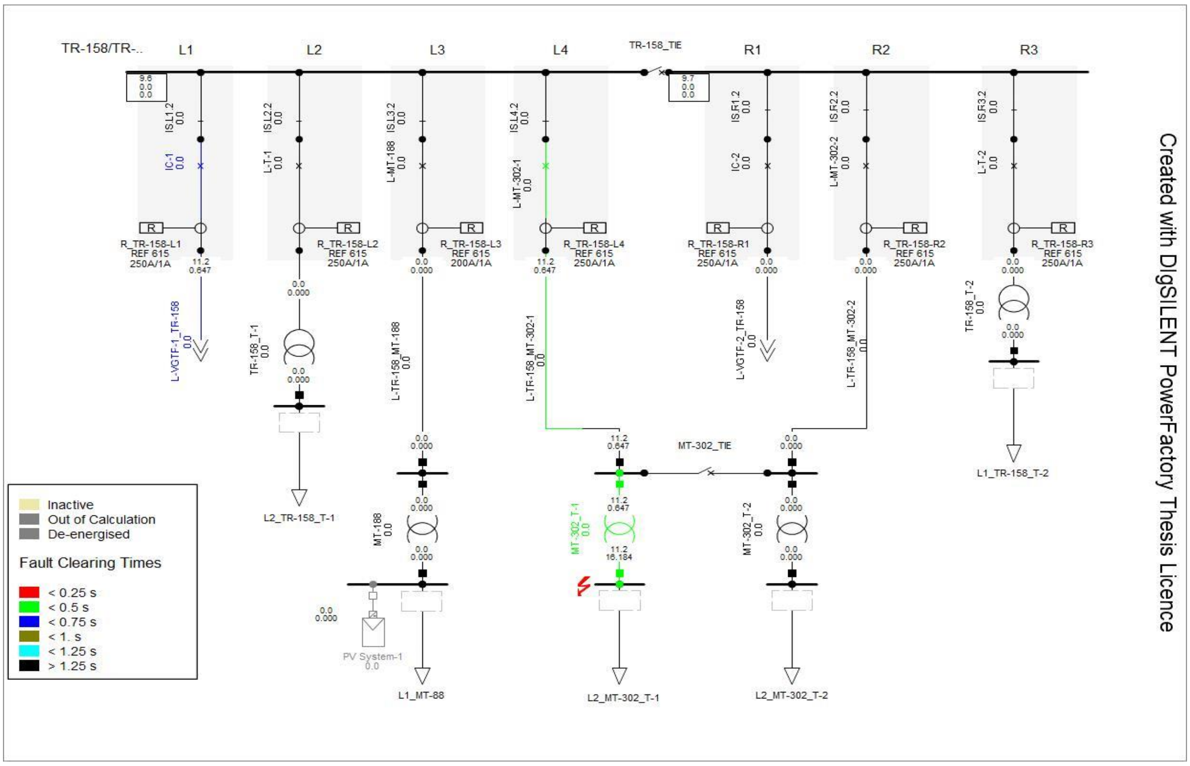


Fig. 25. 3-Ph Short circuit created on LV bus in TR-158 substation

calculated considering the voltage tolerance available on the bus. For the protection system to operate efficiently, the study should be performed for the worst-case scenario, where a heavy fault current can be expected, which is a 3- Ph short circuit fault.

In Powerfactory different types of short circuits can be created. However, for the relay coordination study we need to calculate the maximum short circuit current at the bus. With a click of a mouse, or by choosing the ‘Short-circuit’ option in the ‘Calculation’ toolbox. This is shown here in Fig. 25, a 3 phase short circuit fault is created on the LV bus of the MT-302 transformer. The applied layer in the figure is related to the operation timings of the relays that are already configured in the model. When a fault is created in Powerfactory, the result layer will highlight that particular bus with a red symbol. The parameters on the result layer are selectable from the format node option.

Calculating the short-circuit current at each part of the network is essential for designing a proper relay settings calculation. However, creating short-circuit manually at each location is a cumbersome task and this can be addressed by selecting the ‘All busbars’ option on short-circuit study configuration page. Powerfactory will calculate short-circuit current for the type of fault chosen and will print the results on the output page.

4.2.2 Relay Coordination study

Before start relay coordination study, the developed model must be error-free in Load flow and short circuit studies, current transformers configured in the network are sized according to the connection point and load requirements (ref to the calculation mentioned in 5.1.1), all relays are connected with appropriate current inputs and finally, relay outputs are configured to the circuit breakers as well. The relay coordination study procedure followed in this project can be summarized as follows,

- Initially, to perform successful relay coordination with non-directional overcurrent relays, it is very essential to check the radiality of the network in advance. If there are any circuit breakers (tiebreakers for a 2-infeed bus system) that could form a bi-directional power flow, they need to be identified and kept open.
- Calculate maximum short circuit current at each bus within the network, these values determine the value for high set definite time for the relays.
- In a radial network, relay coordination starts from the lowest voltage level and the devices will be coordinated towards the source from the load.
- As the loads assumed in the network are lumped in nature the protection settings would be mostly similar for every transformer of the same rating. To avoid that and to increase the complexity with the relay coordination, 50% of the load for distribution transformers rating from 400kVA and higher is assumed either as a motor load or a transformer supplying to a commercial consumer.
- Since the objective of this study is to study the relay coordination issues in the network, only maximum fault currents, i.e., 3-Ph short circuits are studied. Hence, no earth fault element is considered active.
- For a transformer on the LV side, 2 stages over current settings calculated, viz. IDMT & DT1 and for the HV side, 3 stage protection is provided, IDMT, DT1 and DT2. DT2 would protect transformers from internal short-circuit faults.
- DT settings for the relays connected with cables is limited to the maximum allowed rated current of the cable (from the cable configuration menu). If the feeder has different cross-

sections cables connected. Nominal current for the lowest cable cross-section is applied for the whole feeder.

Configuration of a typical numerical relay using predefined library model is discussed in earlier sections of this work. However, the values for each protection element used in this model will be calculated individually. There are 325 relays are configured in this model. Discussing the calculation of each of these relay settings is considered impractical for this work, so, the calculation for one typical transformer in TR-158 substation is discussed here and the Fig. 26 shows here the Time of Operation curves for the relays from the LV side to the main incomer feeder.

Rating of TR-158-T-1 transformer - 630 kVA, 10/0.4 kV, Yny0, 5.5%

- Calculating full load current of the LT load connected.

Connected load - 340 kW @ 0.9 pf.
Load current - 340/ (1.732*0.415*0.9*0.9)
= 526 A

Here, a low voltage condition of 0.9 pu is considered to calculate load current in case peak loading (low operating voltages) condition and connected load is 60% of the transformer rating at 0.9 pf.

- Calculate Full load current of the highest motor (if applicable) connected to the LT bus, (considering the 50% of LT load connected is a motor load (assumed))

Motor rating - 170 kW @ 0.9 pf

In KVA - 189 kVA

Load current - 189/ (1.732*0.415*0.9) = 292 A

- Calculate starting current of the motor is estimated with the help of VA burden, ref: IEC 60034-12 [31]

Starting current - 10 * 292 = 2920 A for 5 sec

- IDMT current pickup setting is based on the Full load value (FLA)

Pickup current - 1.05 * FLA = 1.05*526 = 552 A

CT ratio - 2000/1 A

Pickup in Sec - 552/2000 = 0.28

- Current for PSM is – FLA + (highest value among Motor starting current or inrush current of the transformer)

Current value for PSM - 552 + 2920 = 3472 A

Irel - 3472/2000 = 1.736

- Calculate TMS for a tripping time of 6 secs (to allow motor starting time) and the curve selected is IEC Standard inverse, Time dial setting - 1.55

- Calculate DT (time – 0.22 sec) pickup setting – 1.3 times PSM current value.

DT1 setting - 1.3 * 1.736 = 2.26

- Pick-up current for HV side of the transformer

Pick-up current on HV side - 1.05*24 =25.2 A

Pick-up in CT sec (250/1A) - 25.2/250 =0.1

- Current for PSM is – FLA + (highest value among Motor starting current or inrush current of the transformer) – HV side.

Current value for PSM - 3472/25 = 138.88 A

Irel - 138.88/250 = 0.56

- Calculate TMS for a tripping time of 6 secs (above motor starting time) and the curve selected is Normal inverse,

Time dial setting - 1.50

- DT stage-1 (time – 0.22 sec) pickup setting is considered as 1.3 times PSM current value.

DT1 setting - 1.3 * 0.56 = 0.73

- DT stage -2 pickup setting (time- 0.02 sec) - 1.3 times of through fault current on HV side.

DT2 setting - 1.3*647/250 = 3.36

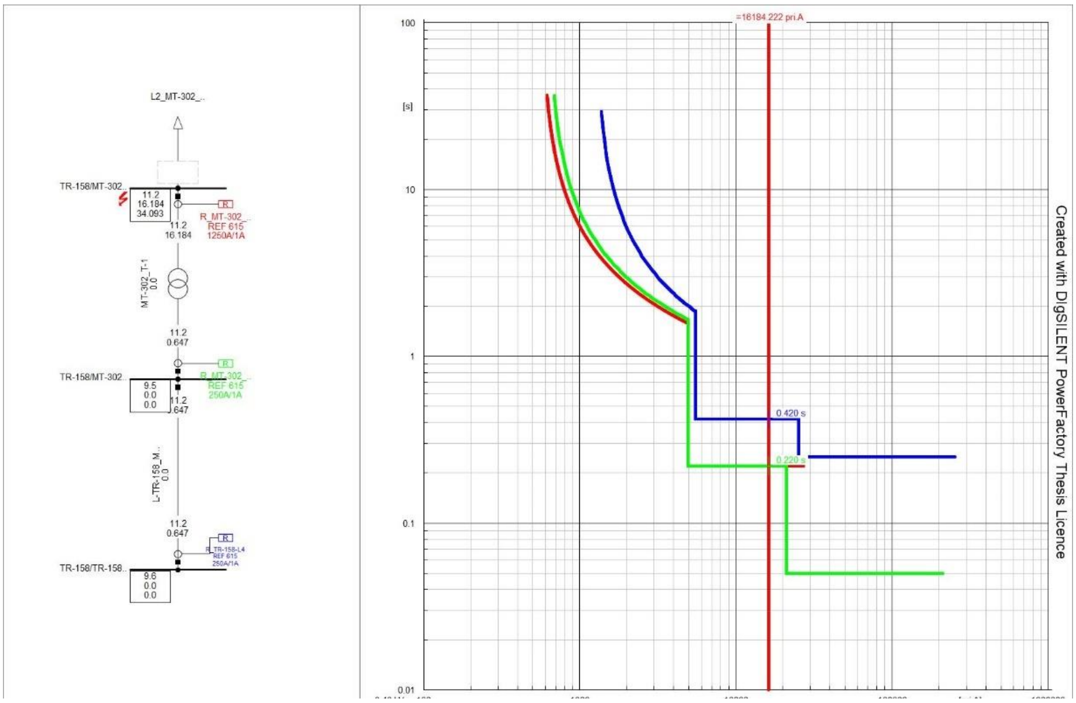


Fig. 26. TOC curves for relays in TR-158 substation

4.3 DER integration, ADP implementation using Python API.

4.3.1 DER Integration and case studies

In the earlier two phases of the project, the Alytus distribution network with a complete working relay is configured. And the same tested for relay operation times by creating faults at the farthest end of the path. Using this exercise relays operation times are fine-tuned and adjustments in relay operation curves are made. As of part of this phase, the most common types of DER, i.e., PV and wind power, are connected at different parts of the network and observed for relay coordination issues, documented issues are studied in detail to provide a solution with the help of Adaptive protection developed in Python IDE.

Maximum disturbance from DER in these study cases was noticed when they are connected at lower SC available bus in the system. To determine the connection point for DER, it is very essential to know both SC availability at the bus as well as the allowed loading for transformer and cables.

4.3.1.1 Study Case – 1 - PV system

Large solar power installations are still uncommon at the distribution level, but there is a clear movement toward more of them. However, in this study lower scale solar system is studied. A PV system of 240 kW is configured on the LV bus of the MT-188 transformer in the TR-158 substation. PV system is configured as a fixed power output device unlike using solar calculations. Since the objective of this study is to study the impact of PV power injection at LV system.

It is to be noted here that the PV system are considered as weak sources of SC power in case of disturbances, due to their complete lack of stored energy. Because of this, the current study is only focused on studying the impact of PV during steady-state condition and to understand this load flow

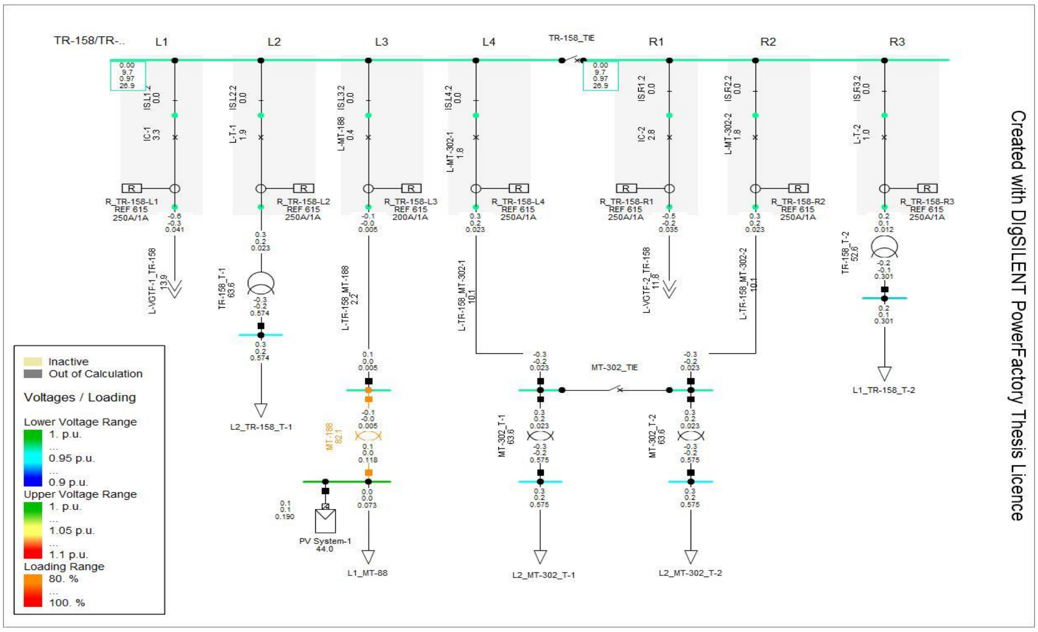


Fig. 27. LDF results with PV system connected at TR-158 substation

study and the results are mapped on the SLD and shown here in Fig. 26 and the loading of the transformer can be observed as in allowed limit.

When the PV system starts its generation at the LV bus, power will be consumed by the load connected on the LV bus and the remaining power would be fed back to the grid through the transformer HV. Here transformer can be seen as a local source (however for a source SC MVA should be higher). As it can be seen from Fig. 27, the transformer is loaded below 85% of its rating while the PV system is in operation.

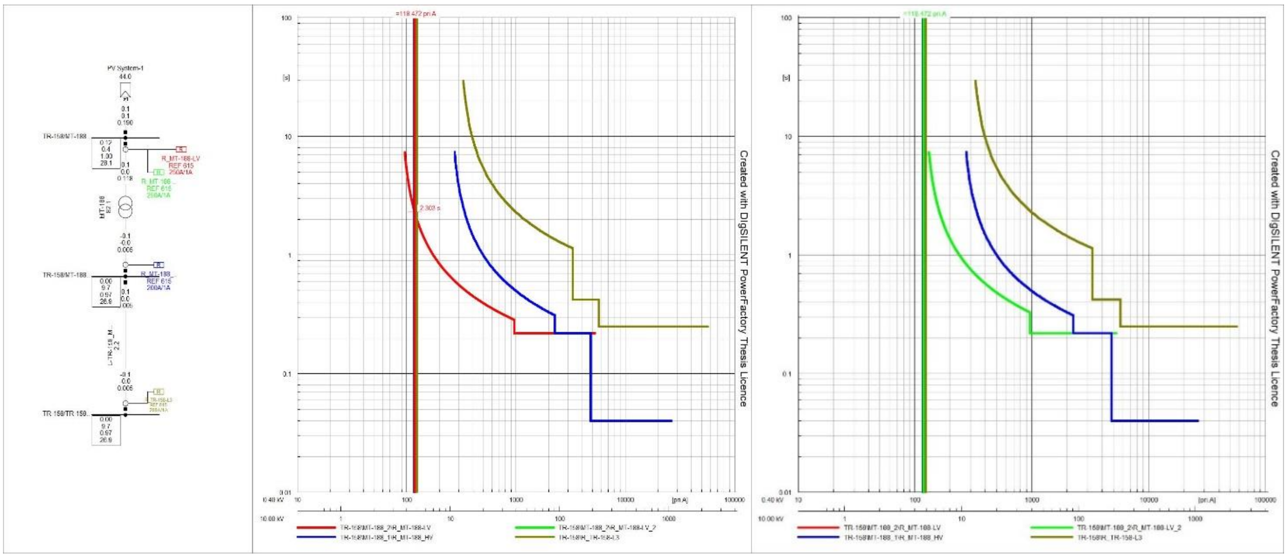


Fig. 28. TOC curves for relays with PV system connected, Load activating IDMT of LV (left), new IDMT settings used with APA (right)

This operation of the network triggered the IDMT operation of the relay on the LV side of the transformer and the same can be noticeable on the left side in Fig. 28 here, the vertical red line here represents the load current on the LV side of the transformer intersecting the LV relay curve (red) at 2.3 sec. This is to be interpreted as when the PV system starts to generate power at 240 kW, the LV side breaker would trip after 2.3 sec. Since it is not an unhealthy operation and the transformer can

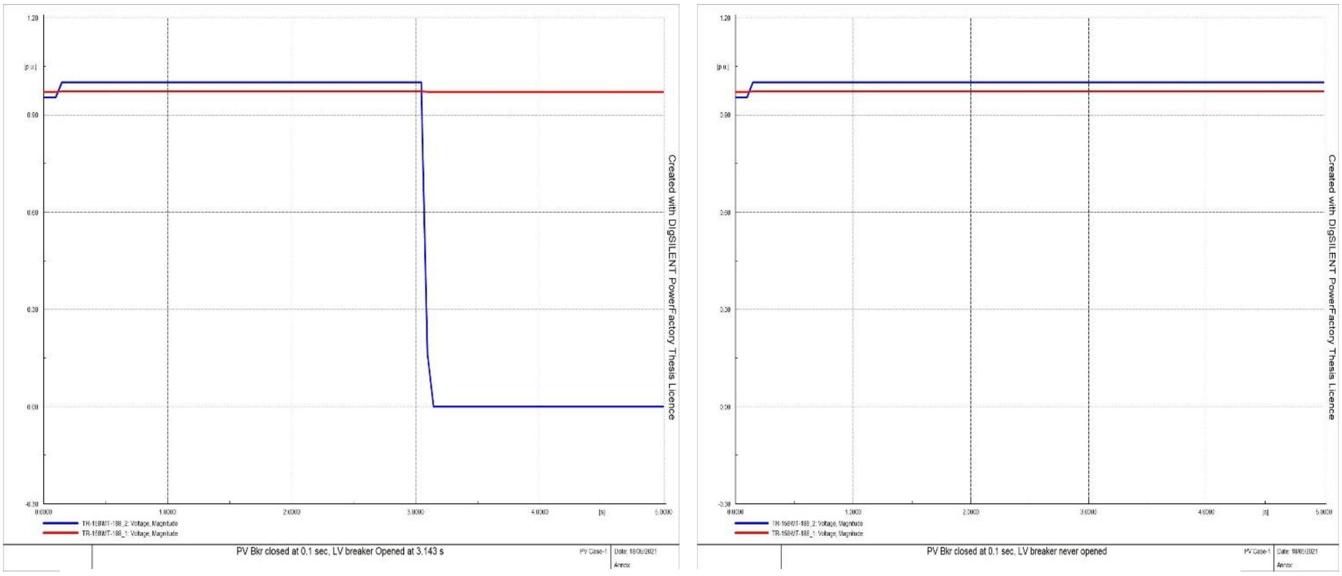


Fig. 29. RMS simulation results for PV system, with old settings (left), new settings (right)

be operated up to 85% of the loading, a new relay is formed at the LV cubicle with revised settings as shown in Fig. 28 right side figure. These new settings will allow the overloading of the transformer while PV is in operation. And the load flow vertical curve is observed to be not intersecting with relay TOC. In Powerfactory, it is not supported to create group settings in a relay unlike in real life numerical relays. So, a separate relay in this project represents a different group setting inside an existing relay in practice.

Time-overcurrent plots in Fig. 28 graphically shows the calculation values on a semi-log graph sheet, however, to check whether the breaker will open after 2.3 secs, RMS/EMT calculations are to be performed with a switching event defined as PV breaker will close after a set period. EMT calculations are used for the understanding of transients in the system, since the objective is to check the RMS voltage profile, the RMS calculation feature of Powerfactory is preferred over.

The RMS simulation function of the Powerfactory gives the ability to study the dynamic behaviour of large-scale systems. Using the RMS balanced feature, long-term transients under balanced network conditions are calculated. Here, a switching event is defined to close the PV breaker after 0.5 sec from the time of simulation starts. This event is defined in the Simulation events feature of the RMS simulation menu in Powerfactory. Before performing any RMS study, it is mandatory to perform initial conditions study on the network. Powerfactory will perform a load flow study through the initial conditions option to load the parameters before RMS simulation.

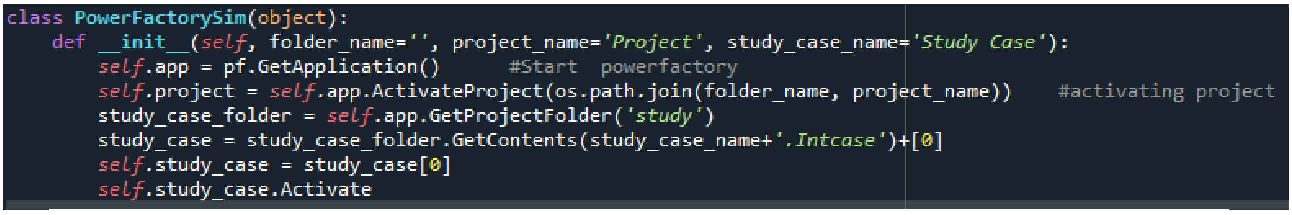
PV CB (Initial)	MT-188 - CB (LV)	MT-188 - CB (HV)	Relay at MT-188-LV		Voltage on LV Bus (in RMS study)
			Relay - 1	Relay - 2	
ON	ON	ON	ON	OFF	0
ON	ON	ON	OFF	ON	Remains at 400 V
OFF	ON	ON	ON	OFF	Reaches to ‘0’ after 2.3 secs
OFF	ON	ON	OFF	ON	Remains at 400 V

Table 1. List of possible scenarios of operation with the PV system

Table-1 mentioned here lists the possible scenarios related to the breaker and relay operating statuses. It can be interpreted from this data that, irrespective of PV CB condition, keeping Relay-1 active results in bus isolation. Scenario -1 from the above table will give an understanding that It is very essential to keep the PV breaker in OFF position as an initial condition. If it is kept in ON condition, during initial condition evaluation, the LV relay will be opened at the starting of the simulation itself. To show the importance of new relay settings in this case study, RMS simulation will be performed twice with alternative relay settings effect. Simulation is run for 5.0 secs and the results are shown in Fig. 29 here. From the fig on left, it can be observed here that, the voltage of LV bus (blue) reaches ‘0’ as a result of isolation of LV breaker and the same is observed to be rectified with the revised relay settings with relay-2 and the same can be noticed on left side figure in Fig. 29. In both cases, the voltage of the HV bus (red line) remains stable as there is no impact of PV integration to the HV side of the transformer.

Implementing APA with Python IDE

RMS simulation gives a clear picture of how important the new relay settings in the context of renewable integration issues. Adaptive protection, these relay settings are to be activated in real-time according to the changes in the network topology. Testing this from the Powerfactory GUI environment is not possible as there is no direct provision for this application is available in the software. For these applications, Powerfactory supports an inbuilt scripting language called DSL and in addition to that it also supports a number of 3rd party programming interfaces and these features were discussed in the earlier part of this work and the list of available interfaces can be seen in ref to Fig. 17 [30] as well.



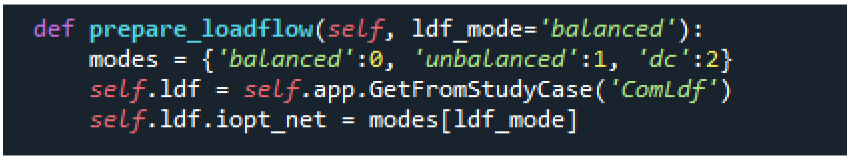
```
class PowerFactorySim(object):
    def __init__(self, folder_name='', project_name='Project', study_case_name='Study Case'):
        self.app = pf.GetApplication()      #Start  powerfactory
        self.project = self.app.ActivateProject(os.path.join(folder_name, project_name))    #activating project
        study_case_folder = self.app.GetProjectFolder('study')
        study_case = study_case_folder.GetContents(study_case_name+'.Intcase')+[0]
        self.study_case = study_case[0]
        self.study_case.Activate
```

Fig. 30. Activating Powerfactory in Python environment

Python is favoured over other API tools to communicate with Powerfactory, It encourages a wide range of libraries for data analysis and it supports both functional as well as object-oriented programming. For this project work, Anaconda distribution with Python 3.8 version pre-installed. All the programming functionalities are written in the Spyder IDE compiler. Some of the basic functionalities used in this work are referred to from [30].

Powerfactory can be imported into and run from an external Python script in engine mode, eliminating the need for a graphical user interface. Engine mode allows Powerfactory features to be simply integrated into any Python program. Upon importing into the Python environment, it's critical not to start Powerfactory directly or with any other instances. Before beginning the project, it's critical to update the Python version's position in Powerfactory's settings page.

Python programming using in this project is divided into 2 sections, one where all functions required for the program are defined as an object and these were called to perform actions in the main program as per the requirement of the algorithm. Fig. 30 here shows the function defined to import Powerfactory into python and activating project and study cases. Attributes used such as ‘ActivateProject’, ‘GetProjectfolder’ etc., are predefined with particular functionality and the description of the syntax and application are documented in [32].

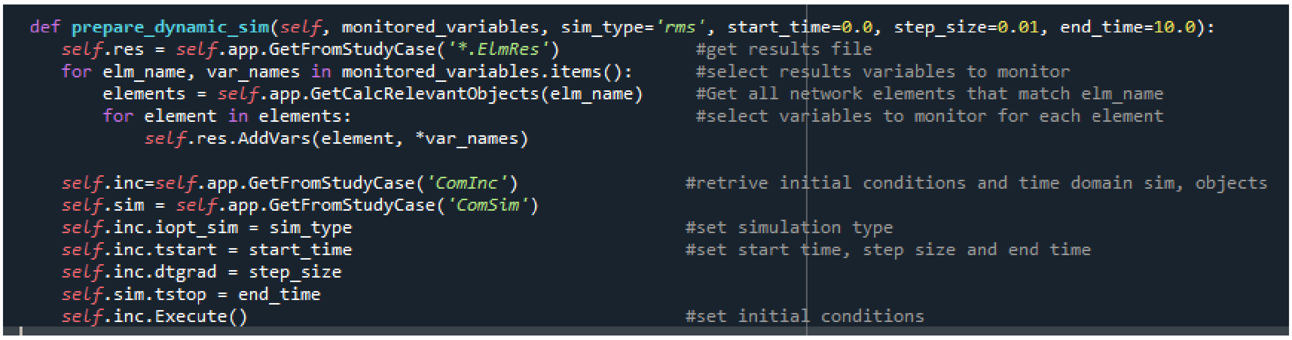


```
def prepare_loadflow(self, ldf_mode='balanced'):
    modes = {'balanced':0, 'unbalanced':1, 'dc':2}
    self.ldf = self.app.GetFromStudyCase('ComLdf')
    self.ldf.iopt_net = modes[ldf_mode]
```

Fig. 31. Running LDF with Python API

After activating the project and study cases into python, using the function shown in Fig. 31, load flow calculations will be performed. The attribute ‘iopt_net’ in script defines the type of the mode used for load flow study, where 0 for ‘balanced’, 1 for ‘unbalanced’ and 2 for ‘dc’ load flow studies. All our calculations in this project are performed with balanced load flow studies.

The function shown in Fig. 32 is created to perform RMS simulations using python API. After importing the active study case from the project, variables that are intended to monitor for elements in the result file are called. By executing the ‘ComInc’ object, python performs initial calculations for the RMS study and the attributes of the RMS simulation settings are passed on to the function as variables. This allows us to have control over simulation parameters, such as step size, start time and end time.



```python
def prepare_dynamic_sim(self, monitored_variables, sim_type='rms', start_time=0.0, step_size=0.01, end_time=10.0):
    self.res = self.app.GetFromStudyCase('*.ElmRes')            #get results file
    for elm_name, var_names in monitored_variables.items():     #select results variables to monitor
        elements = self.app.GetCalcRelevantObjects(elm_name)    #Get all network elements that match elm_name
        for element in elements:                                #select variables to monitor for each element
            self.res.AddVars(element, *var_names)

    self.inc=self.app.GetFromStudyCase('ComInc')               #retrive initial conditions and time domain sim, objects
    self.sim = self.app.GetFromStudyCase('ComSim')
    self.inc.iopt_sim = sim_type                               #set simulation type
    self.inc.tstart = start_time                               #set start time, step size and end time
    self.inc.dtgrad = step_size
    self.sim.tstop = end_time
    self.inc.Execute()                                         #set initial conditions
```

Fig. 32. RMS simulation with Python API

In the main program for PV load flow evaluation using RMS simulation works as shown in Fig. 33 here, after importing the project, study cases and relays of the LV circuit breaker for ‘MT-188’ substation, a display message will be prompted to ask whether APA should be ON or OFF. The input for this message will be considered to alter the relay settings and continue with RMS simulations.

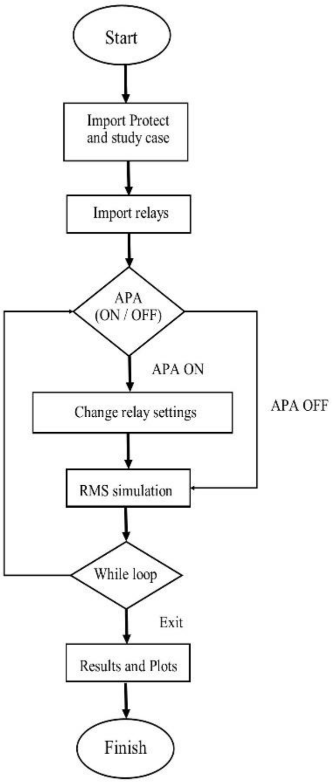


Fig. 33. Flow chart of Python API operation

A while loop is used to perform RMS simulations multiple times with or without changing relay settings. This is to avoid performing initial calculations, importing project and study cases for each time we run python for a single RMS calculation.

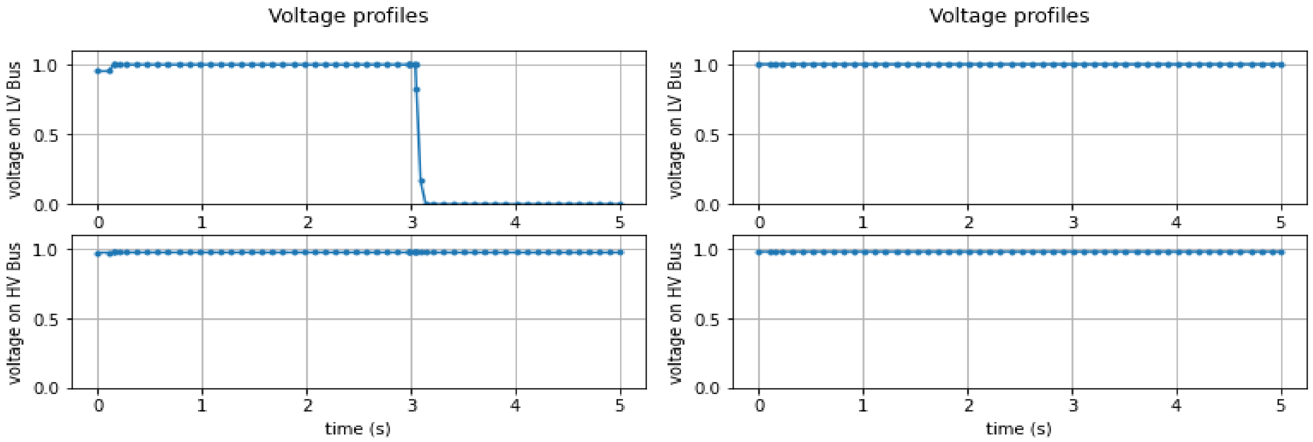


Fig. 34. Results of RMS simulation from Python API – without APA (left), with APA (right)

Results from monitored values are stored in ‘lists’ inside python. Lists in python are similar to array or matrix in other programming languages. Fig. 34 here shows the voltage for LV and HV buses plotted separately in both cases. These plots are identical to the results discussed earlier, ref to Fig. 29. This shows that the algorithm implemented inside the python is working well with the current case study.

4.3.1.2 Study Case – 2 – Wind Power

Since the PV case study cannot give a clear idea of relay coordination issues during SC condition, another case with wind power integration is studied here. PCC of wind power at SP-4 resembles the case discussed in Fig. 12 [13].

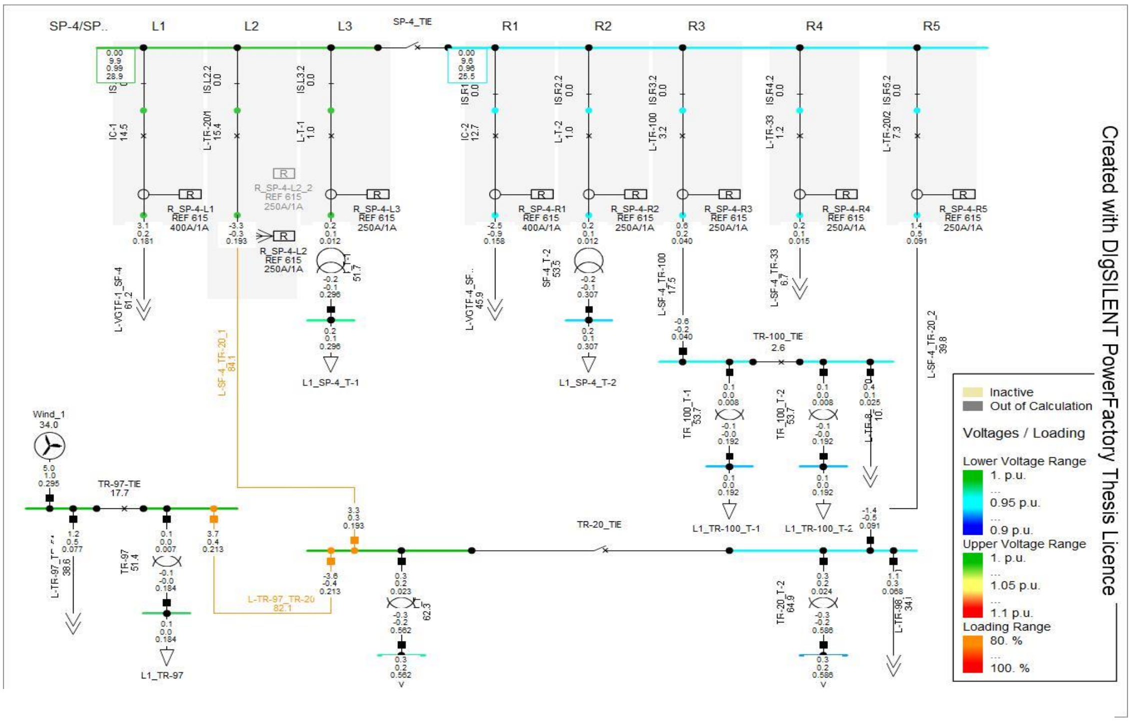


Fig. 35. LDF results with wind power at SP-4 substation.

The power rating of the wind is fixed at 5 MW, operating with a power factor of 0.98. The rating is decided following the loading of the line and the feeder. Fig. 35 here shows the load flow results with the integration of wind at busbar TR-97_1 in the model.

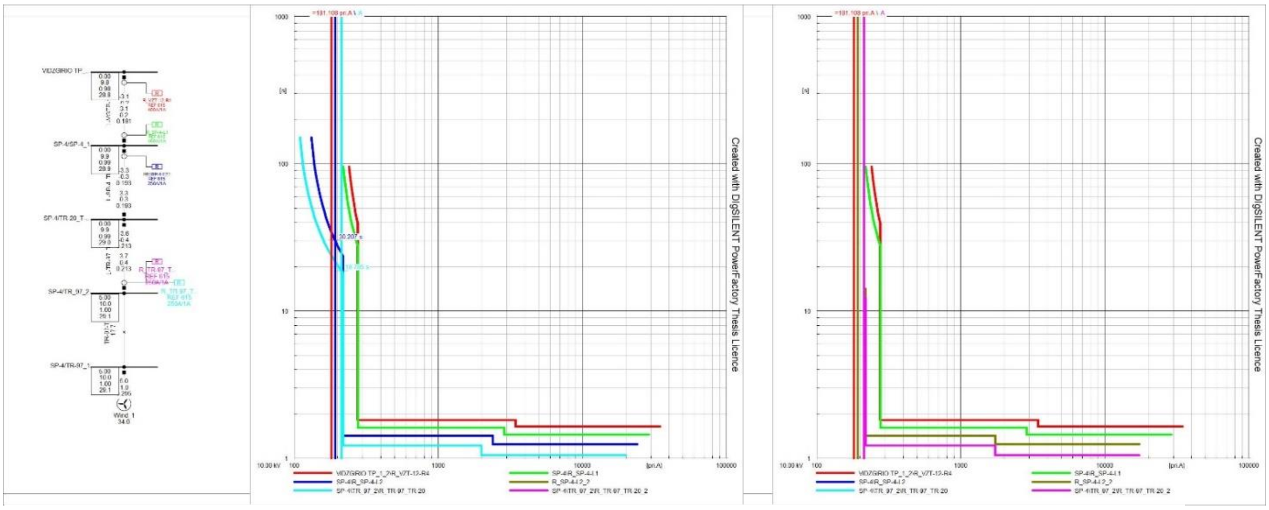


Fig. 36. TOC curves for the feeder relays with LDF reults

When load flow results are plotted on TOC curves for the entire feeder, it was observed that the IDMT settings of the relays protecting cable 'L-TR-97_TR-20' and the feeder 'SP-4-L2_2' are found to be intersecting. Since the available range for IDMT of these two relays is very less, it is considered to be disabled in new relay settings, results in two-stage DT relay settings for both cable and feeder relays.

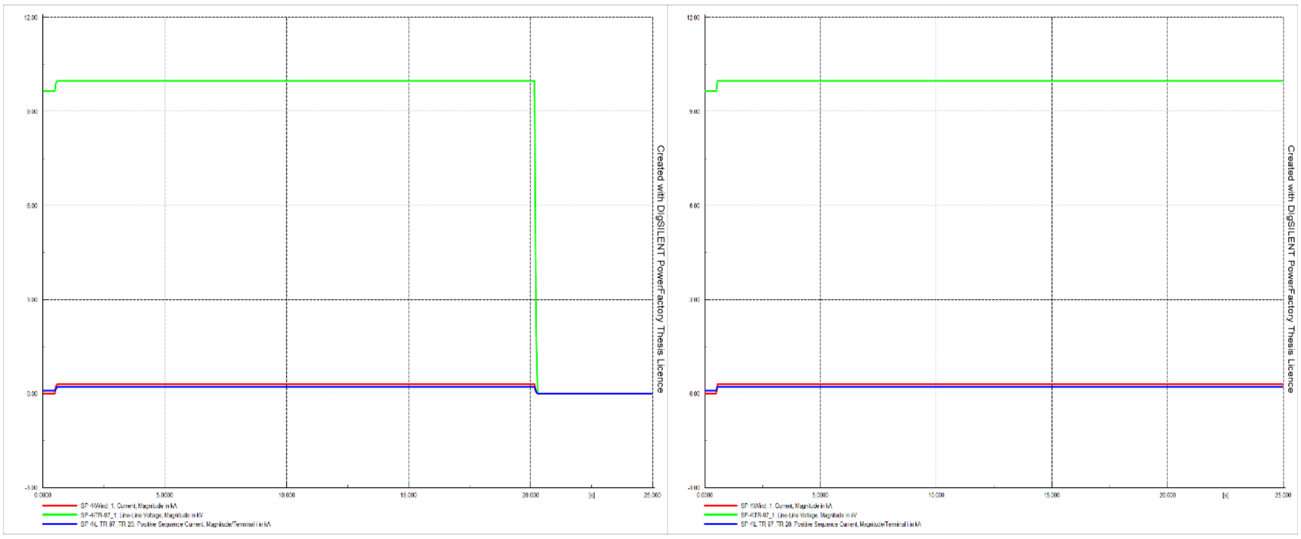


Fig. 37. RMS simulation with wind power connected – Feeder breaker trips (left), feeder breaker remain operational (right)

The same operation is cross-checked using the RMS simulation of wind power, as can be observed in Fig. 37. On the left side, the current profile (green) through the cable is observed to have plummeted to zero after a time duration of 18 secs from the event the wind power is switched on. The sudden increase in voltage and currents at 0.5 secs after the simulation start is the results of the closing wind power breaker. On the right side of Fig. 37[13], it can be observed that wind power has remained connected to the bus and the new relay settings proposed are observed to be effective.

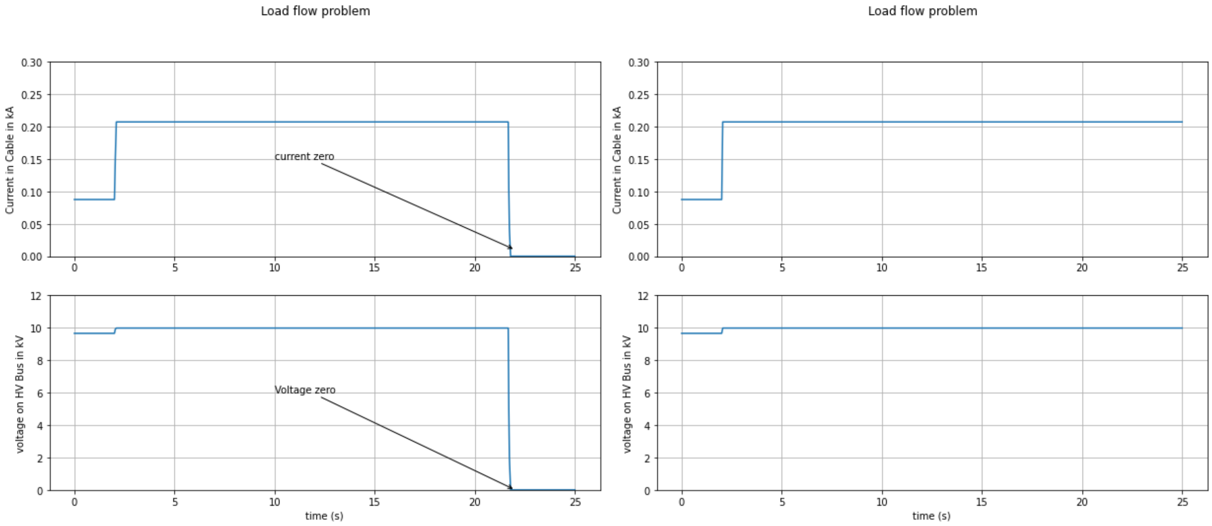


Fig. 38. RMS simulation for load flow results. Without APA (left), with APA (right)

Similar results are observed from the RMS simulation of load flow studies with Python API and the same are shown in Fig. 38 here. As it can be noticed here, the voltage and current zero annotation on the left plot shows the breaker is opened after approximately 19 secs from the time the wind power is switched on. The process flow for checking this simulation for this study is similar to the one shown in Fig. 33 earlier.

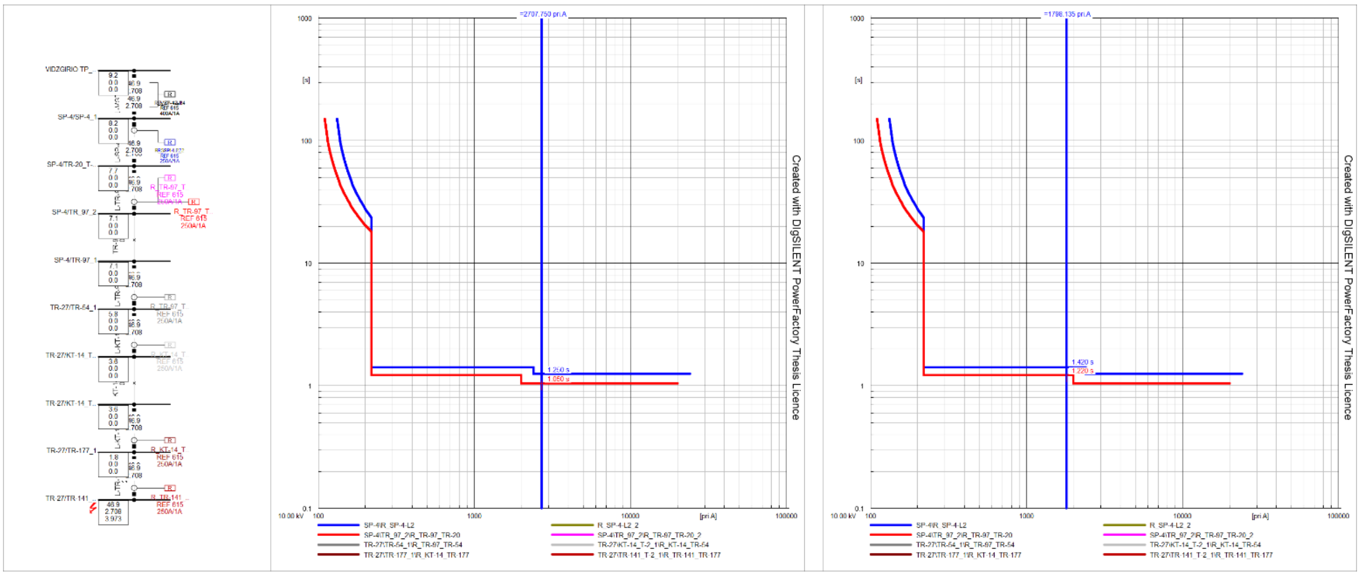


Fig. 39. TOC curves for the feeder relays with SC results. Without wind power (left), with wind power (right)

In addition to the load flow problem, the high SC capacity of wind powers can cause relay coordination issues in an already existing system upon integration. This can be better interpreted with the help of TOC curves as shown in Fig. 39 here. The entire feeder is plotted on the left side of the graph for representation purpose here. As the difference between left and right curves are observed, it is quite evident that the presence of wind power has resulted in a delayed response from upstream relays.

The right side of the plot in Fig. 39 shows the revised relay setting TOC curves that allow the inclusion of wind power into the relay coordination study. To understand the influence of the wind power on relay operating time at the L2 feeder, RMS simulation for SC fault on the end of the feeder is studied. A 3-Ph fault on bus ‘TR-141-T-2_1’ is created, and all the relays from the faulted bus till feeder are kept in out of service as the objective is to see the influence of wind power on the relay at feeder starting during fault at the end of it and the results are plotted and shown in Fig. 40 here.

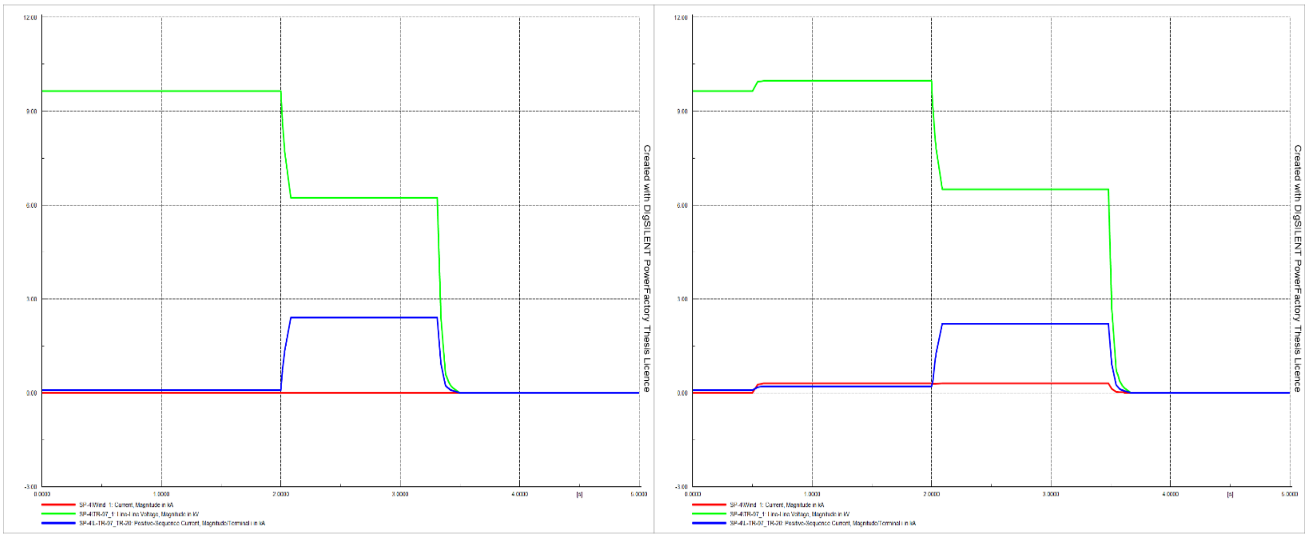


Fig. 40. RMS simulation with SC on TR-141T-2_1 bus, without wind power (left), with wind power (right)

On the left side plot, the current and voltage profiles are observed to be constant until the fault event is initiated. This is because the power is remaining constant during the simulation. When a fault is initiated after 3.49 secs, the breaker at the L2 bay opened, resulting in current through the ‘L-TR-97_TR-20’ cable (green) to zero and the voltage on the bus as well as for the wind power terminals are plummeted to ‘0’ as well. Whereas for the right side of the plot, wind power is switched on before the creation of SC on the farthest end of the feeder. The new timing for the operation of the relay at the ‘L2’ feeder is observed to be 3.66 secs. The delay in the time of operation is due to less fault

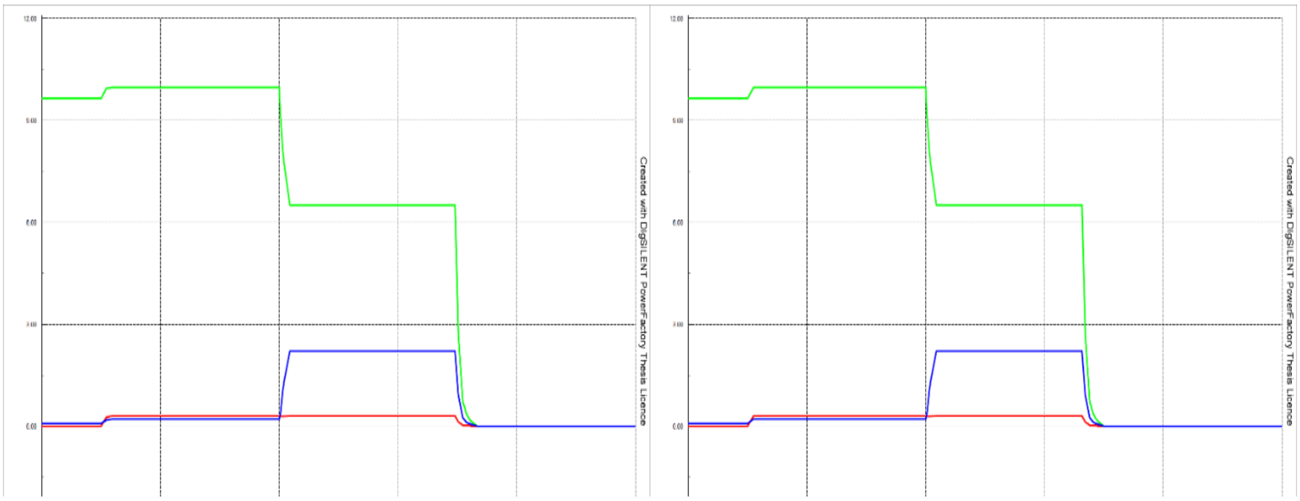


Fig. 41. RMS simulation with SC on TR-141 bus with wind power, without APA (left), with APA (right)

contribution from the main source, which results in slower relay operation. With the activation of new relay settings at the ‘L2’ feeder, the same case study will be repeated to observes the difference in relay operation times. The results of this RMS study are plotted here in Fig. 41.

As it can be observed here in both of these plots in Fig. 41 shows the operation of the wind power before the SC event. The small change in current and voltages is distinguishable at the beginning of the simulation. The left plot shows the time of operation for the relay with earlier settings and the right plot for the relay with new settings to accommodate wind power. The revised relay settings in relay isolate the far end fault almost at the same time duration as in the case with no wind power at all, i.e., at 3.49 sec after the fault is initiated. This result shows that the new relay settings are essential for holding the coordination time intact with the new power source on the feeder.

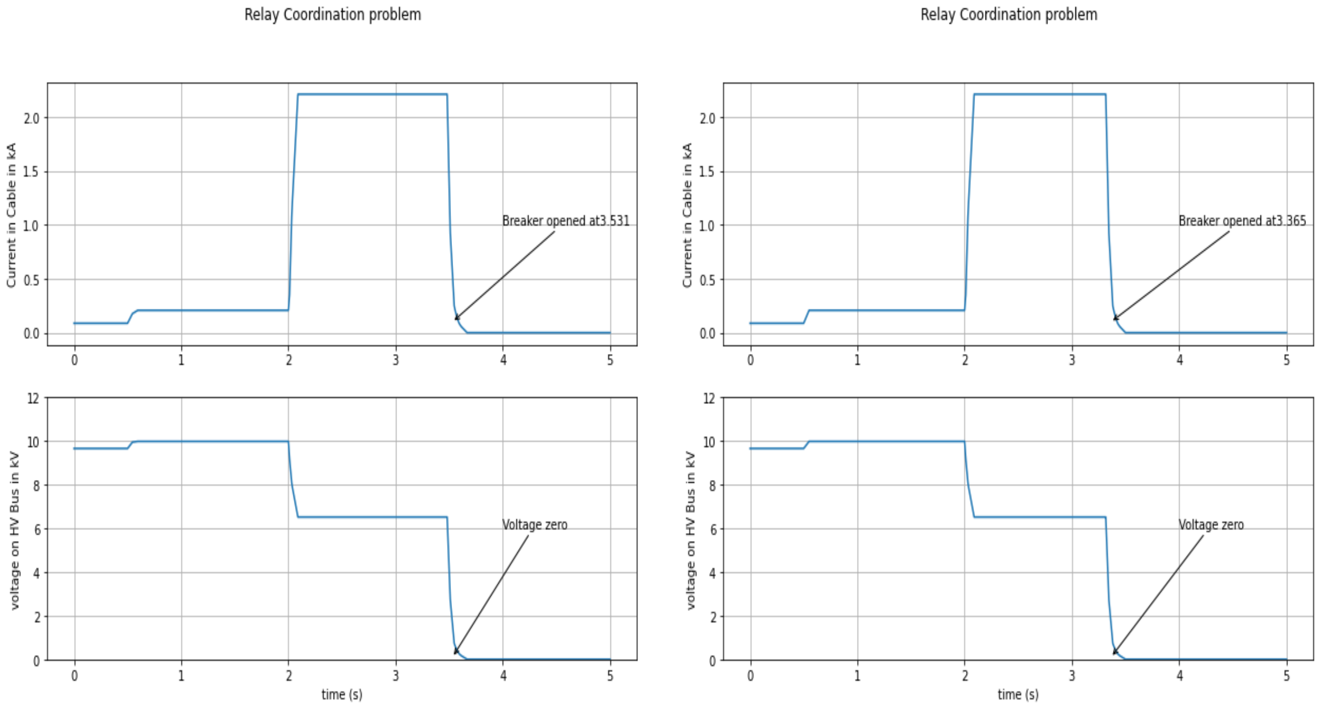


Fig. 42. RMS simulation results from python with SC on TR-141 bus with wind power, without APA (left), with APA (right)

With the help of python API, the same study is repeated, however, the difference from RMS simulation with Powerfactory GUI and Python is that, when the APA is option is selected, the script developed in the program will automatically change the relay settings and run the RMS simulation. In addition to the flow chart process discussed in Fig. 33, for this case study and an additional option for the SC event control is used. This gives the flexibility to use the same program for both LDF study and SC study as well. The results from the SC study conducted with Python API are shown in Fig. 42 and they can be noticed to be of the same profiles shown in the RMS simulation in Fig. 41 earlier. This proves that the proposed APA program works well with both the studies discussed in this project.

Conclusions

In this project, the influence of the DER integration over relay coordination is studied in detail. It was observed that the inclusion of DER at the distribution level results in either misoperation or delayed operation of protection depending on the connection arrangement.

1. When a connected Photovoltaic system on the LV side of the MT- 188 transformer starts power production, the relay settings of the LV breaker are found to be compromised. By studying the load flow results matched with the TOC curves, it was observed that when the PV array produces its rated power, LV CB will trip on overload after 2.3 secs. This case was validated with the help of RMS simulation.

2. Since the loading of the transformer with the PV connection at LV is below the acceptable loading, the overload element for the LV breaker is disabled in the proposed APA relay settings. These revised relay settings are checked with the RMS simulation, and it was found that the PV array remained in operation. The same results were checked with the help of the ADP program in Python and the results from the simulation are found to be identical to the one plotted in Powerfactory.

3. Unlike PV array, wind system can feed power in both steady-state and dynamic states (SC contribution to faults) due to its inertia. To study the influence of wind power on the existing network in steady-state and dynamic state conditions, a 5 MW wind power is connected at TR-97_1 bus on a 10kV long feeder. Load flow results have shown that power injected by 5 MW wind power results in overload operation of relays at main feeder relay after 18 secs of the closing breaker at the wind, this results in disruption of power feeding to the entire radial feeder.

4. It was verified with RMS simulation in Powerfactory that the feeder relay trips after 18.3 secs from the time the Wind power breaker is switched on. As a solution to this, revised relay settings with disabled overload element (IDMT) is configured and validated with the RMS simulation. Using python API, revised relay settings are enforced during the simulation whenever Wind power is switched on with APA and the plots from python are observed to be identical to the RMS simulation results.

5. SC fault at the end of the feeder with a wind power connected would result in the delayed operation of the main feeder relay. When a 3-Ph fault is created on TR-141-T-2_1 without wind power, the relay at L2 bay is operated at 3.49 secs, and when wind power is active, the same relay sensed fault at 3.66 sec. This delay is due to reduced fault contribution with wind power connected. In both, cases relays between L2 and TR-141 are kept ‘out of service’ to observe the impact. This has been cross-checked with both RMS and Python simulations.

6. Revised relay settings for the relays are proposed to accommodate the wind power operation and to avoid delayed tripping when wind power is active. With the help of RMS simulation, these relay settings are validated in the Powerfactory environment. Using an Adaptive protection scheme switching scheme of relay settings during the simulation process is checked. With the Adaptive protection for the same fault, feeder relay L2 has observed to operate at 3.49 secs, hence satisfying the requirements of coordination intervals of the network.

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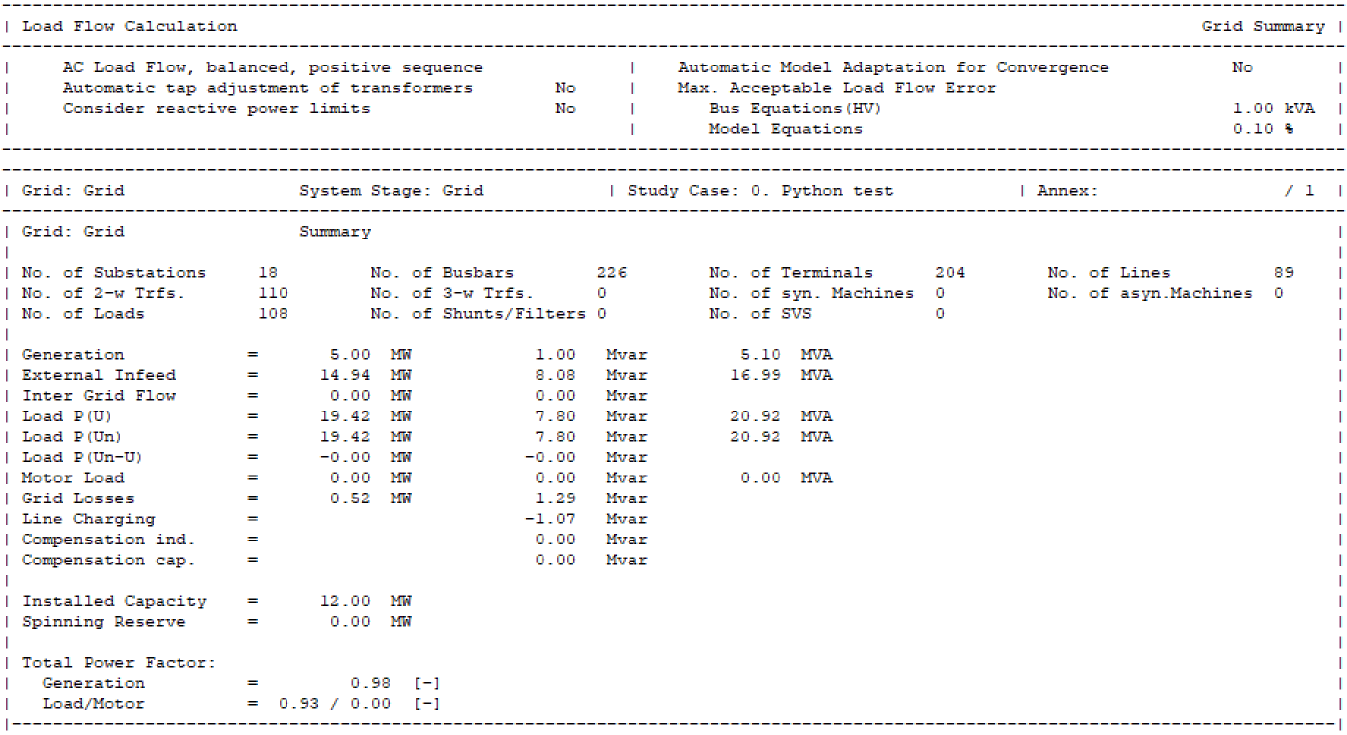
Appendix

Grid summary and the load flow results of each substation in the model are shown here,



```
-----------------------------------------------------------------------------------------------------------------------------------
| Load Flow Calculation                                                                                               Grid Summary |
-----------------------------------------------------------------------------------------------------------------------------------
|     AC Load Flow, balanced, positive sequence                | Automatic Model Adaptation for Convergence           No        |
|     Automatic tap adjustment of transformers        No       | Max. Acceptable Load Flow Error                                 |
|     Consider reactive power limits                  No       |    Bus Equations(HV)                                 1.00 kVA  |
|                                                              |    Model Equations                                   0.10 %    |
-----------------------------------------------------------------------------------------------------------------------------------
-----------------------------------------------------------------------------------------------------------------------------------
| Grid: Grid                    System Stage: Grid             | Study Case: 0. Python test              | Annex:               / 1  |
-----------------------------------------------------------------------------------------------------------------------------------
| Grid: Grid                    Summary                                                                                           |
|                                                                                                                                 |
| No. of Substations      18         No. of Busbars        226         No. of Terminals      204         No. of Lines           89 |
| No. of 2-w Trfs.        110        No. of 3-w Trfs.       0          No. of syn. Machines  0           No. of asyn.Machines   0  |
| No. of Loads            108        No. of Shunts/Filters  0          No. of SVS            0                                     |
|                                                                                                                                 |
| Generation             =      5.00  MW            1.00   Mvar       5.10  MVA                                                   |
| External Infeed        =     14.94  MW            8.08   Mvar      16.99  MVA                                                   |
| Inter Grid Flow        =      0.00  MW            0.00   Mvar                                                                  |
| Load P(U)              =     19.42  MW            7.80   Mvar      20.92  MVA                                                   |
| Load P(Un)             =     19.42  MW            7.80   Mvar      20.92  MVA                                                   |
| Load P(Un-U)           =     -0.00  MW           -0.00   Mvar                                                                  |
| Motor Load             =      0.00  MW            0.00   Mvar       0.00  MVA                                                   |
| Grid Losses            =      0.52  MW            1.29   Mvar                                                                  |
| Line Charging          =                         -1.07   Mvar                                                                  |
| Compensation ind.      =                          0.00   Mvar                                                                  |
| Compensation cap.      =                          0.00   Mvar                                                                  |
|                                                                                                                                 |
| Installed Capacity     =     12.00  MW                                                                                          |
| Spinning Reserve       =      0.00  MW                                                                                          |
|                                                                                                                                 |
| Total Power Factor:                                                                                                             |
|   Generation           =        0.98   [-]                                                                                      |
|   Load/Motor           =  0.93 / 0.00   [-]                                                                                     |
|---------------------------------------------------------------------------------------------------------------------------------|
```

Fig. Grid summary results from Powerfactory output window.

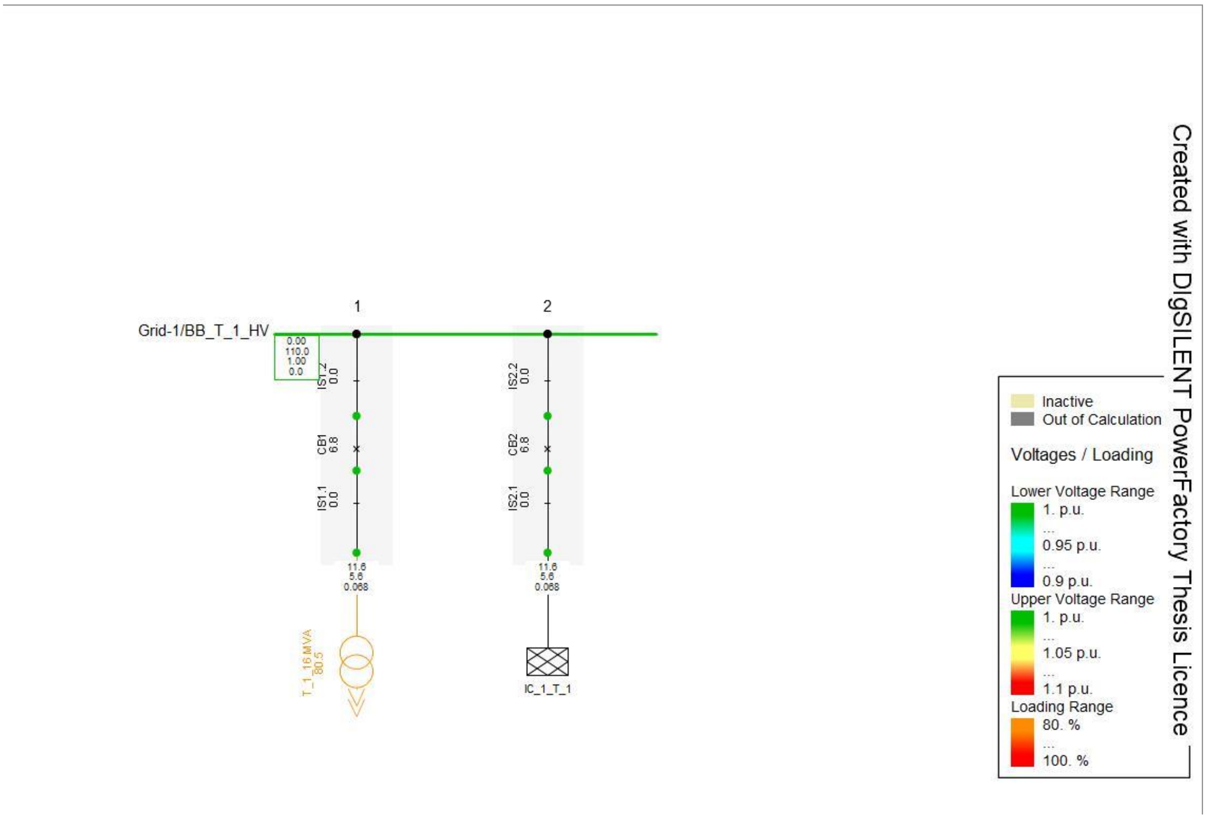


Fig. Load flow results of 16 MVA Transformer -1 bus.

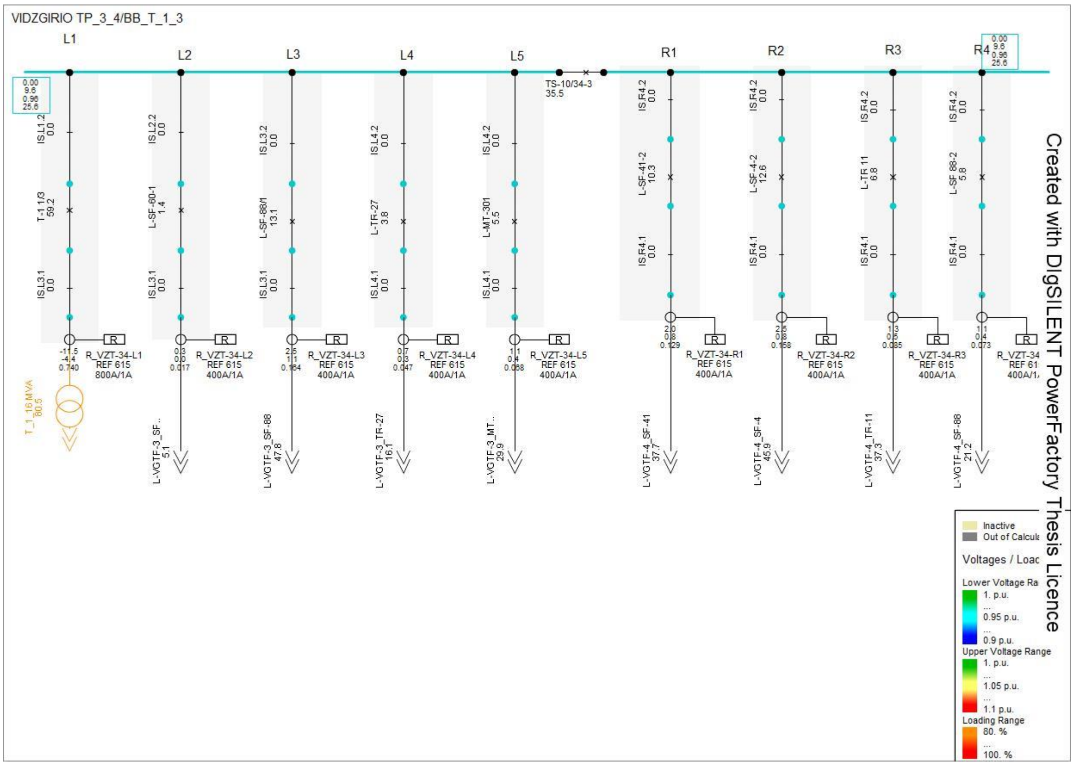


Fig. Load flow results for VIDZIGIRIO TP Bus 3 and 4 buses

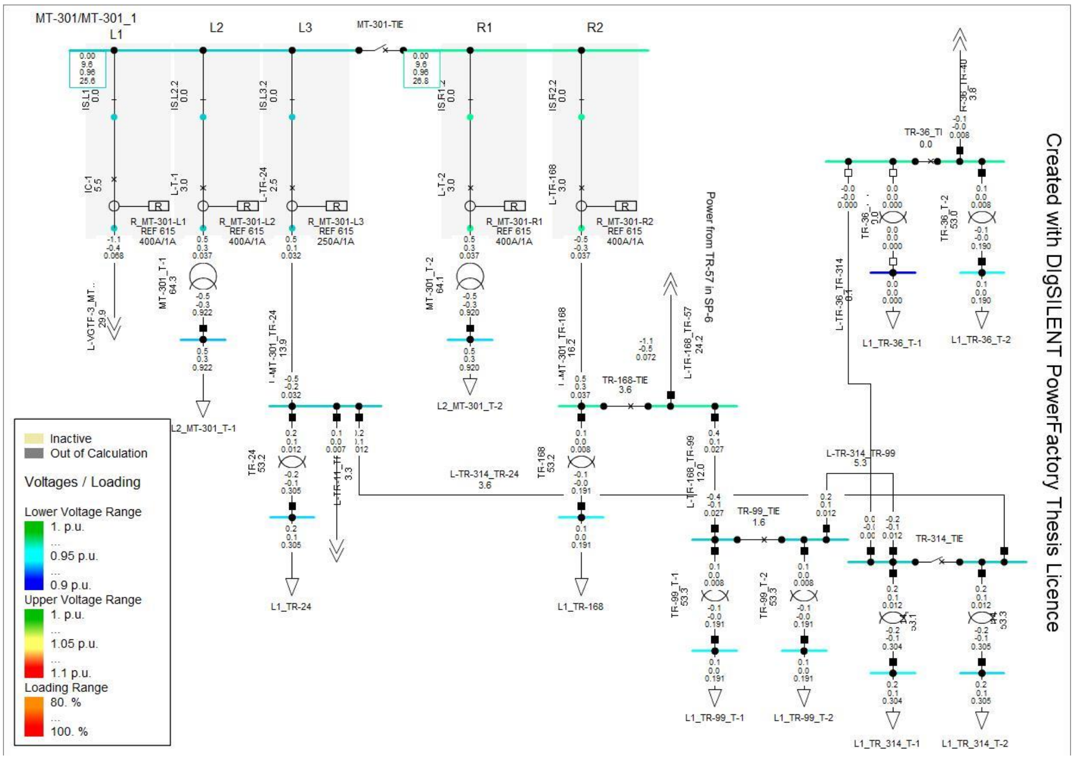


Fig. Load flow results for MT 301 substation

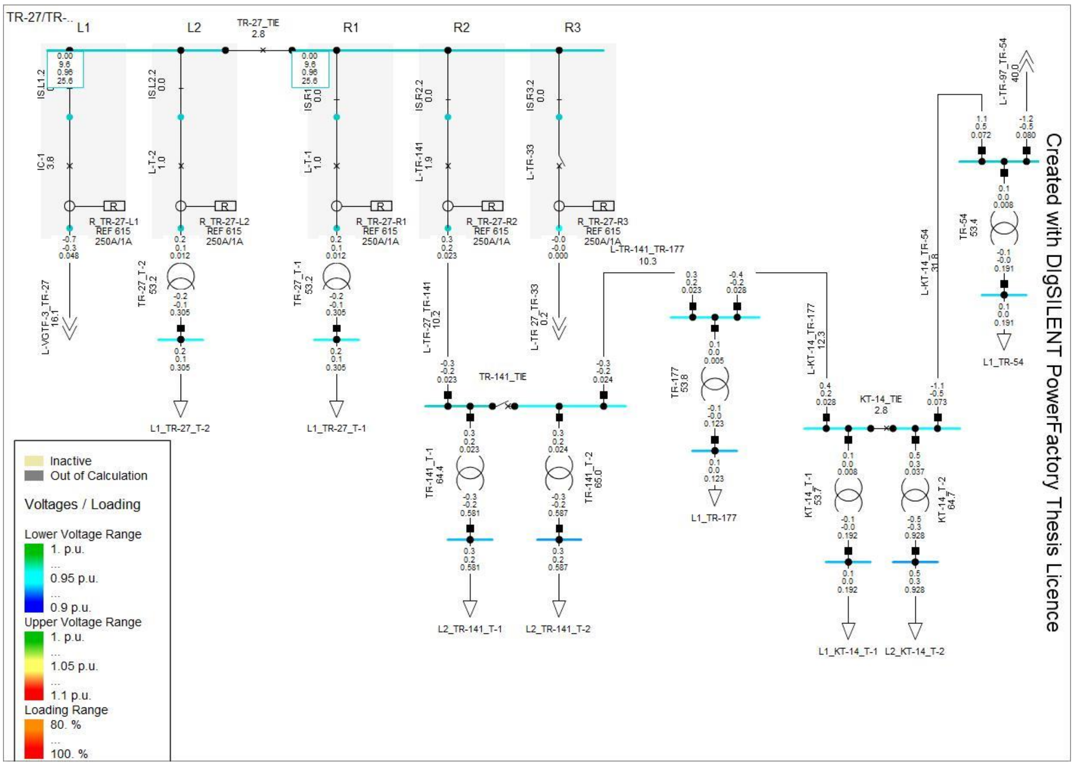


Fig. Load flow results for TR-27 substation

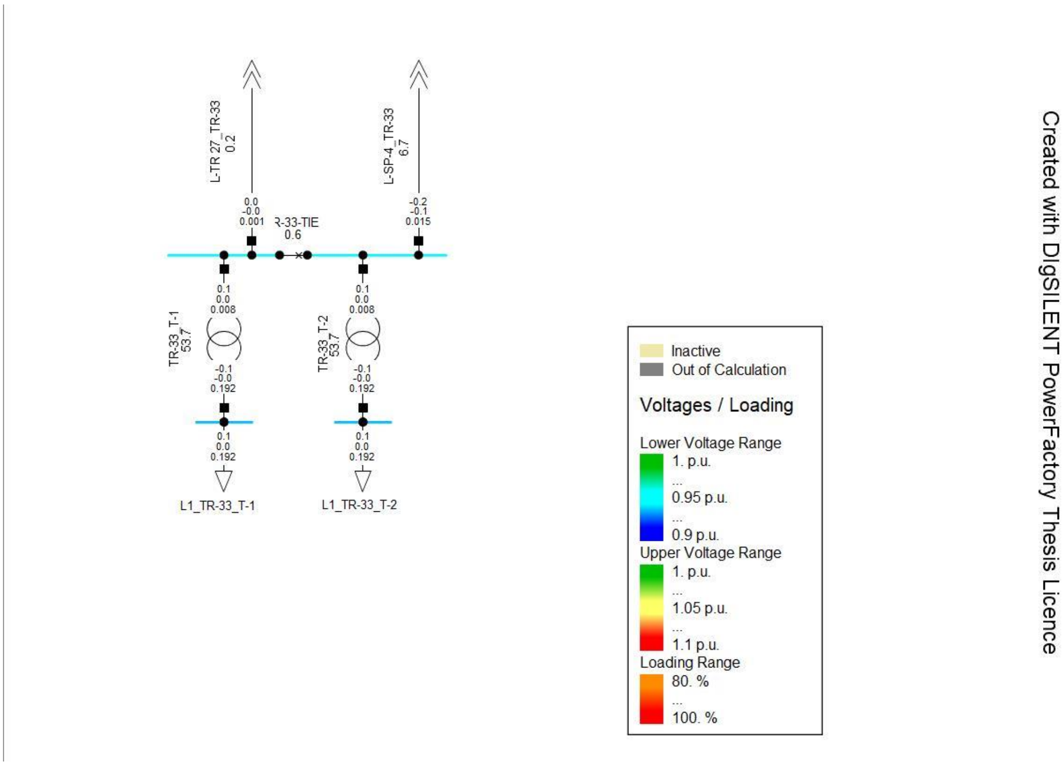


Fig. Load flow results for TR-33 substation

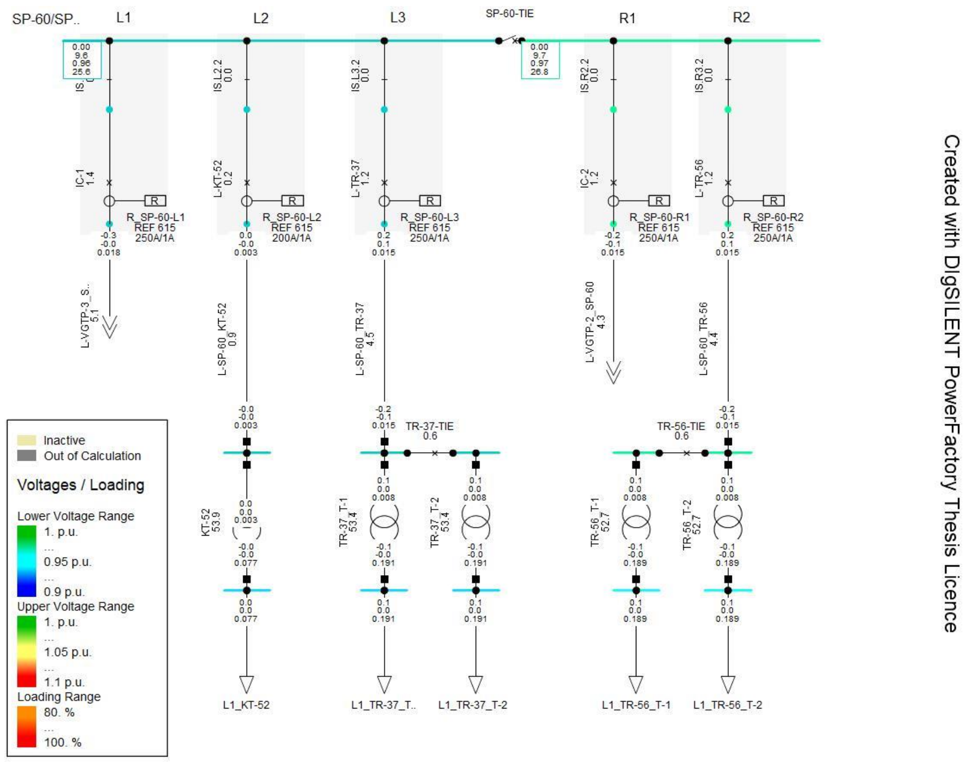


Fig. Load flow results for SP-60 substation

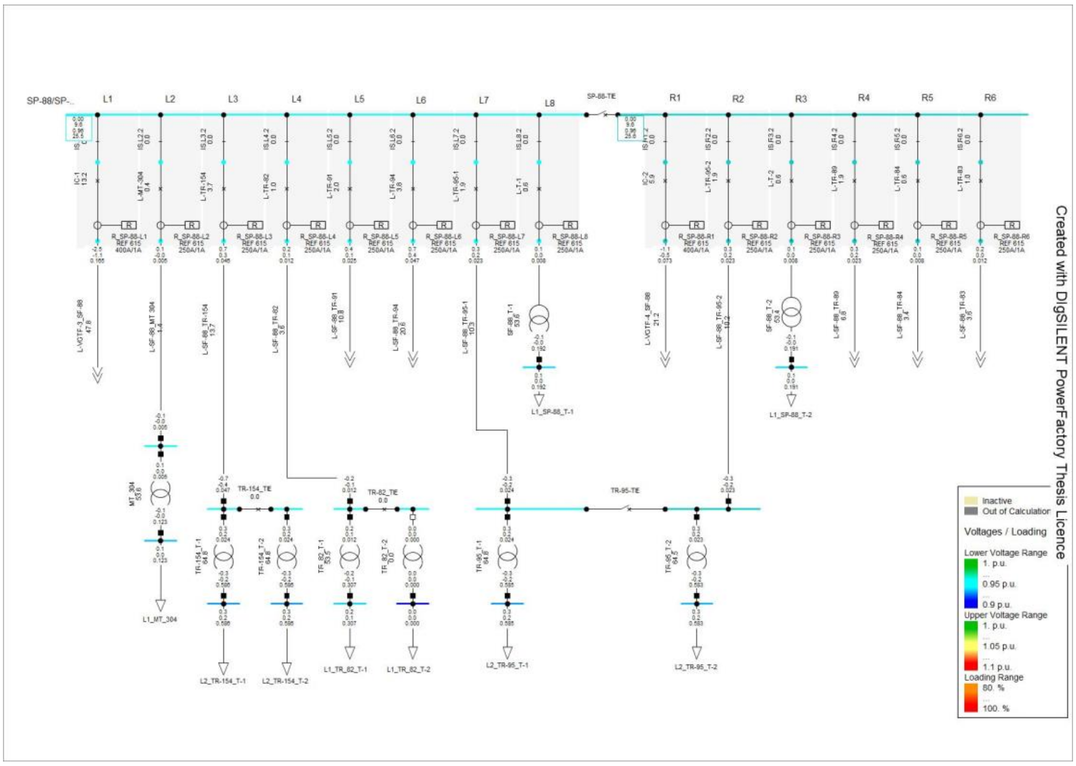


Fig. Load flow results for SP-88 substation

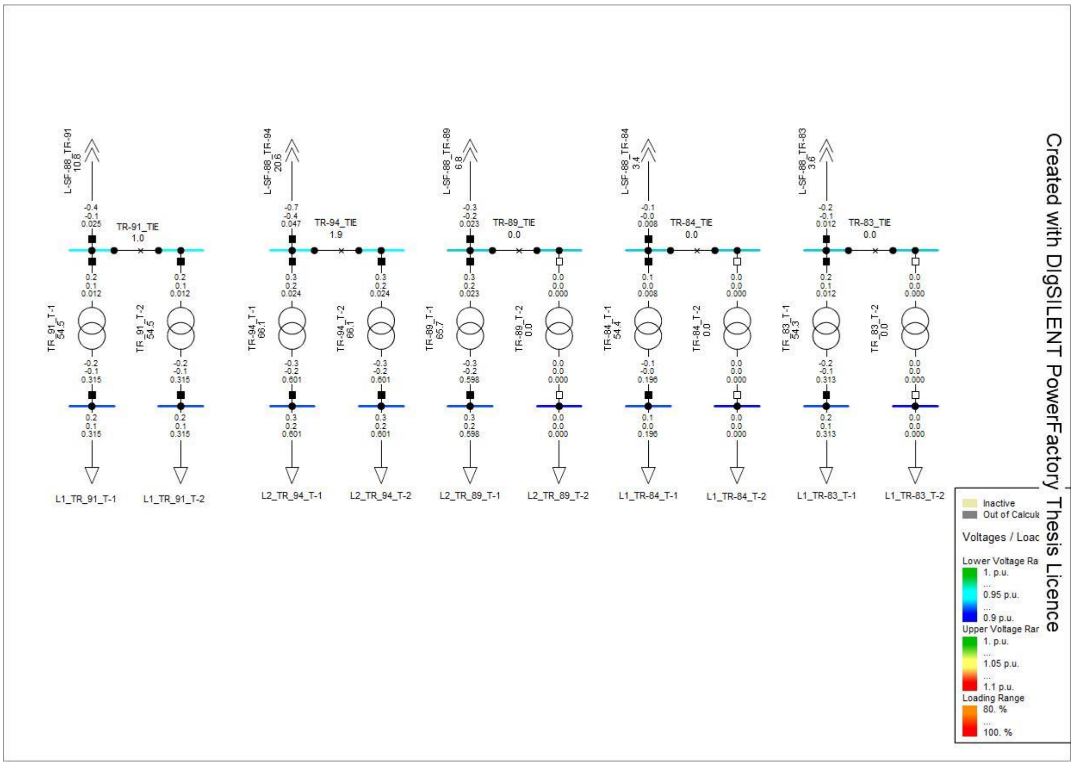


Fig. Load flow results for SP-88 (LV) substation

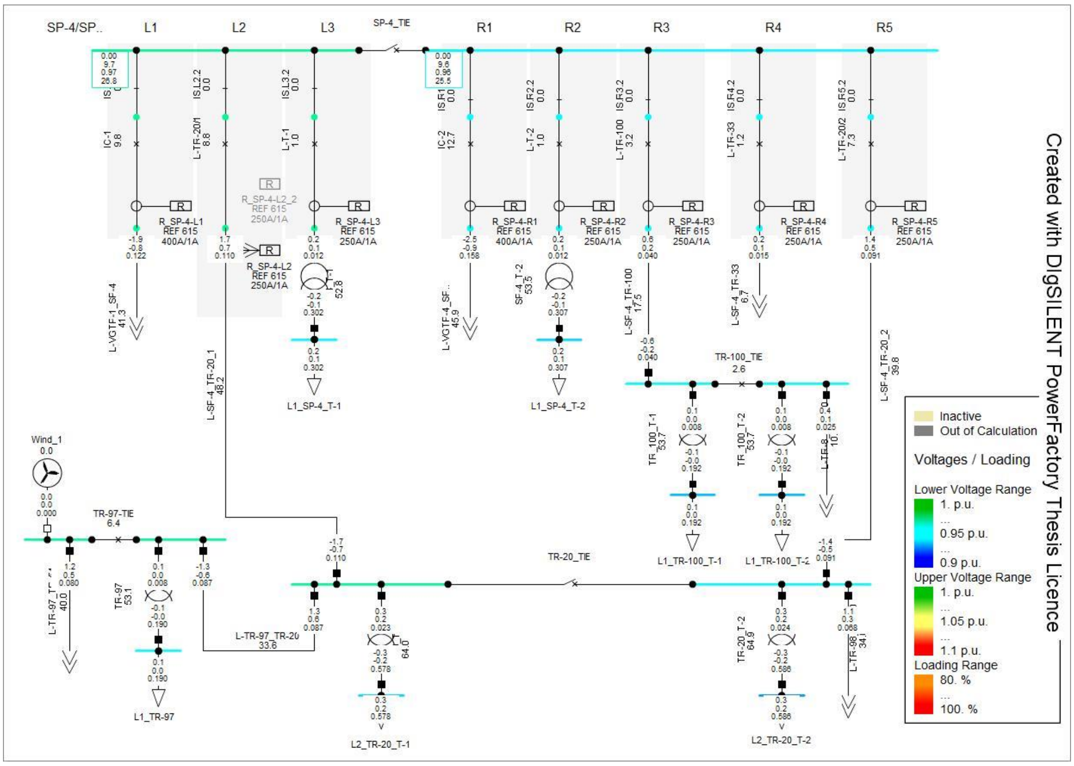


Fig. Load flow results for SP-4 substation

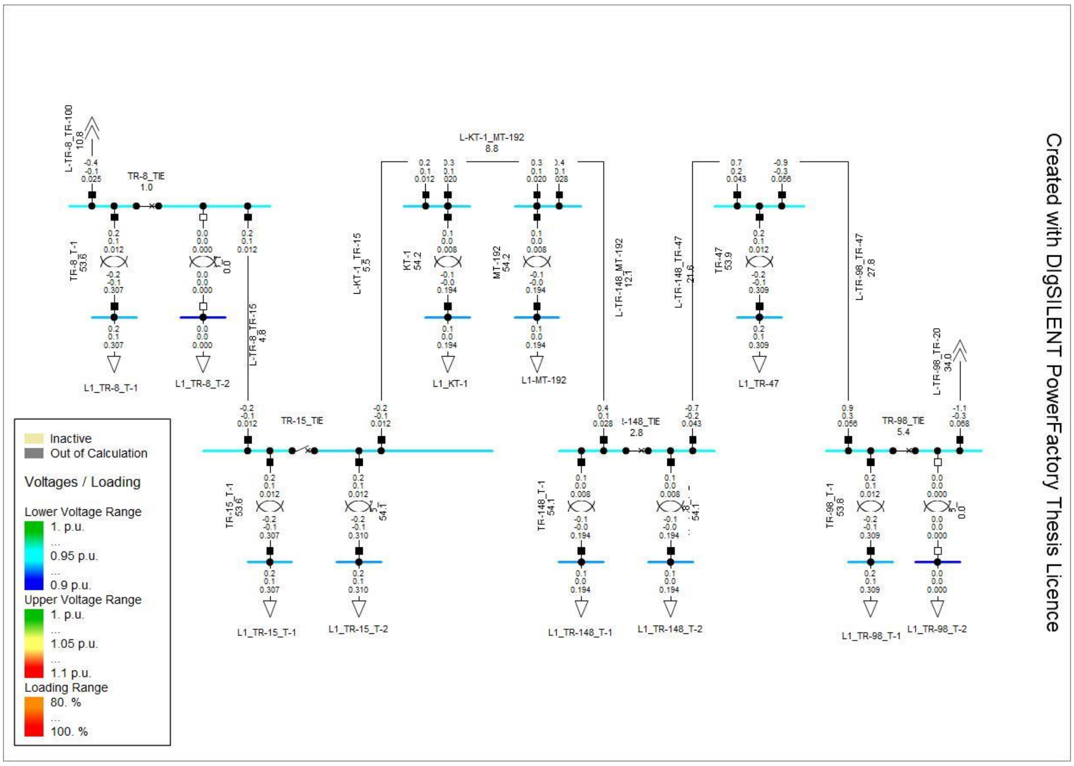


Fig. Load flow results for SP-4 (Contd) substation

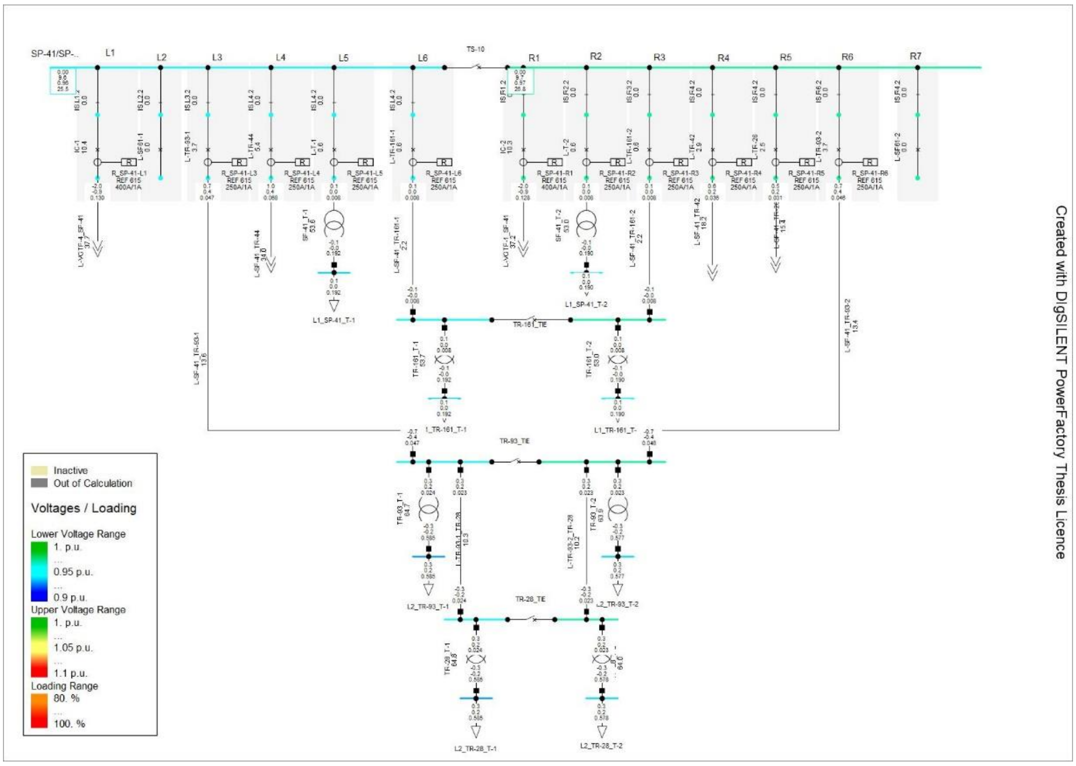


Fig. Load flow results for SP-41 substation

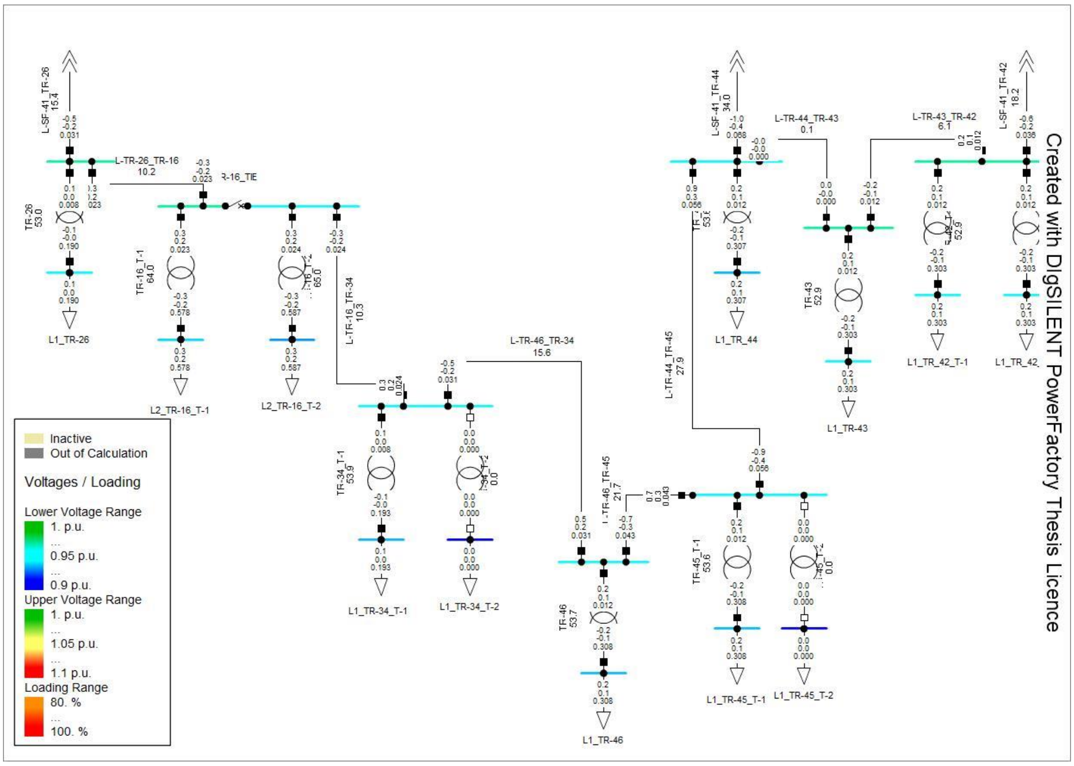


Fig. Load flow results for SP-41 (Contd) substation

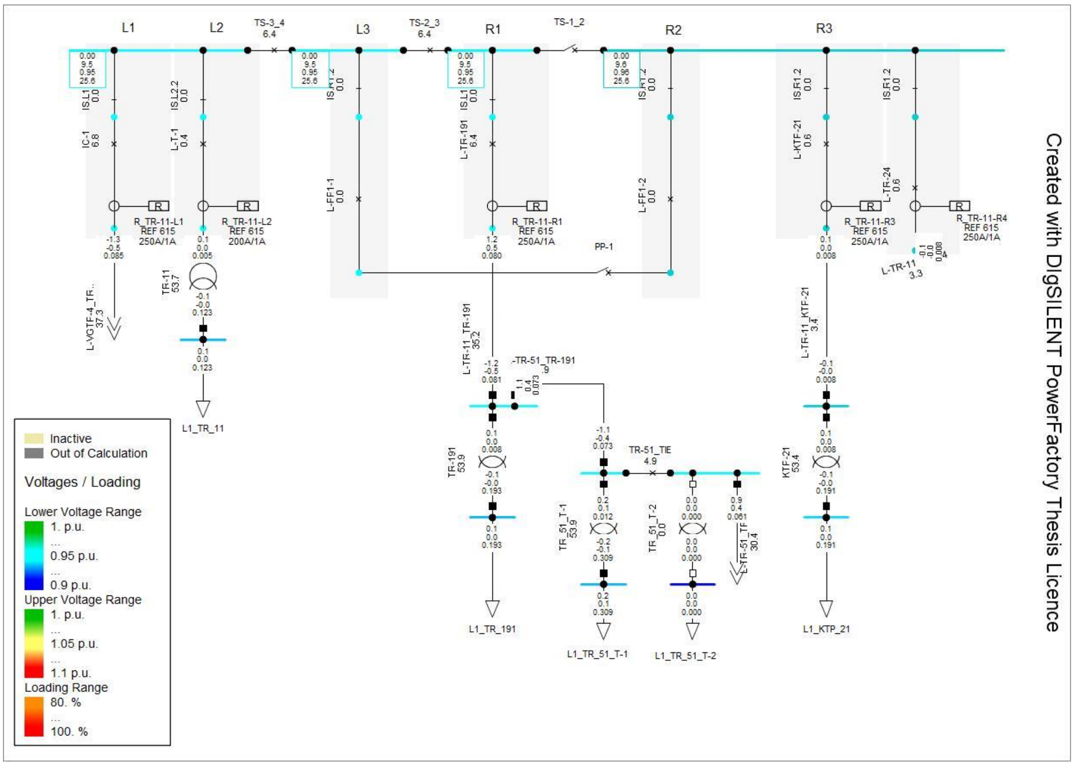


Fig. Load flow results for TR-11 substation

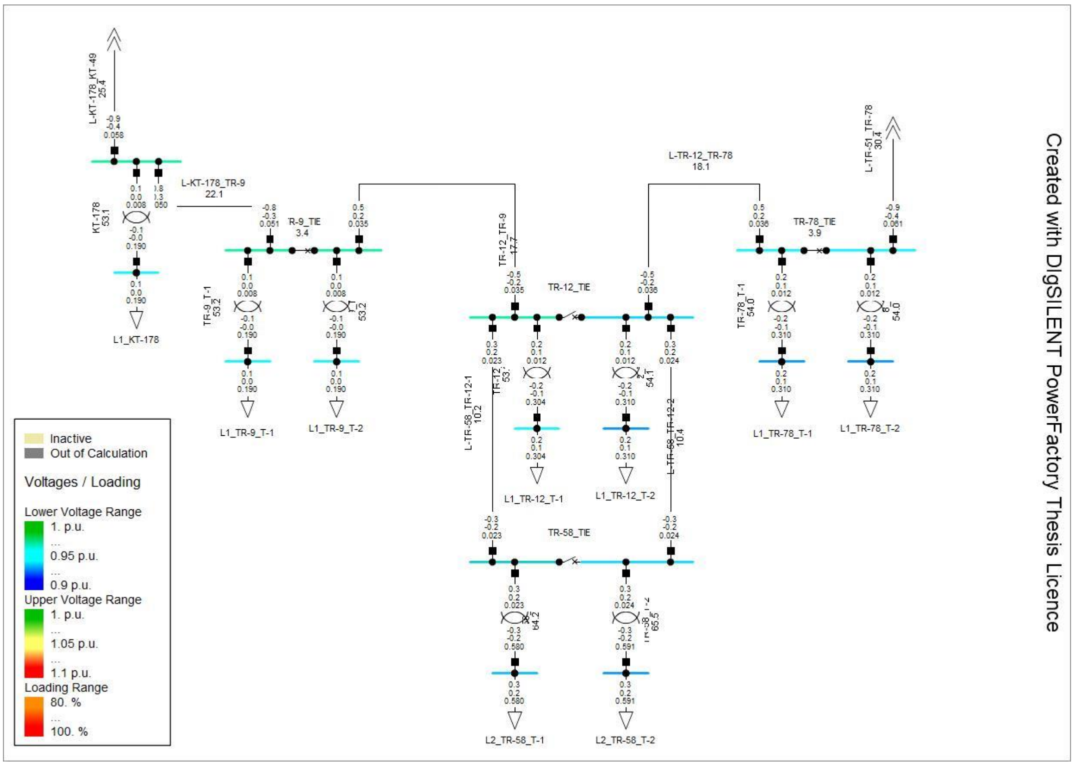


Fig. Load flow results for TR-11 (Contd) substation

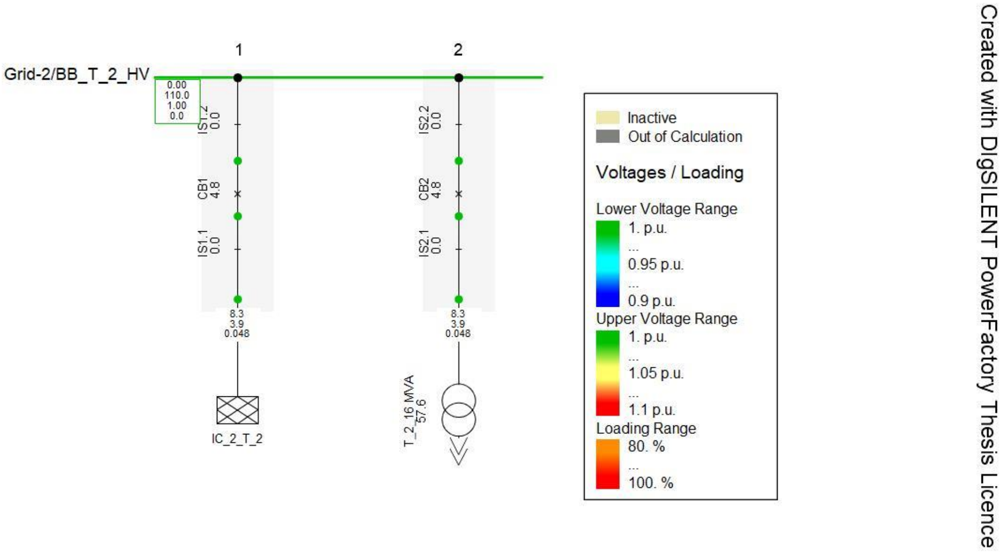


Fig. Load flow results of 16 MVA Transformer -2 bus.

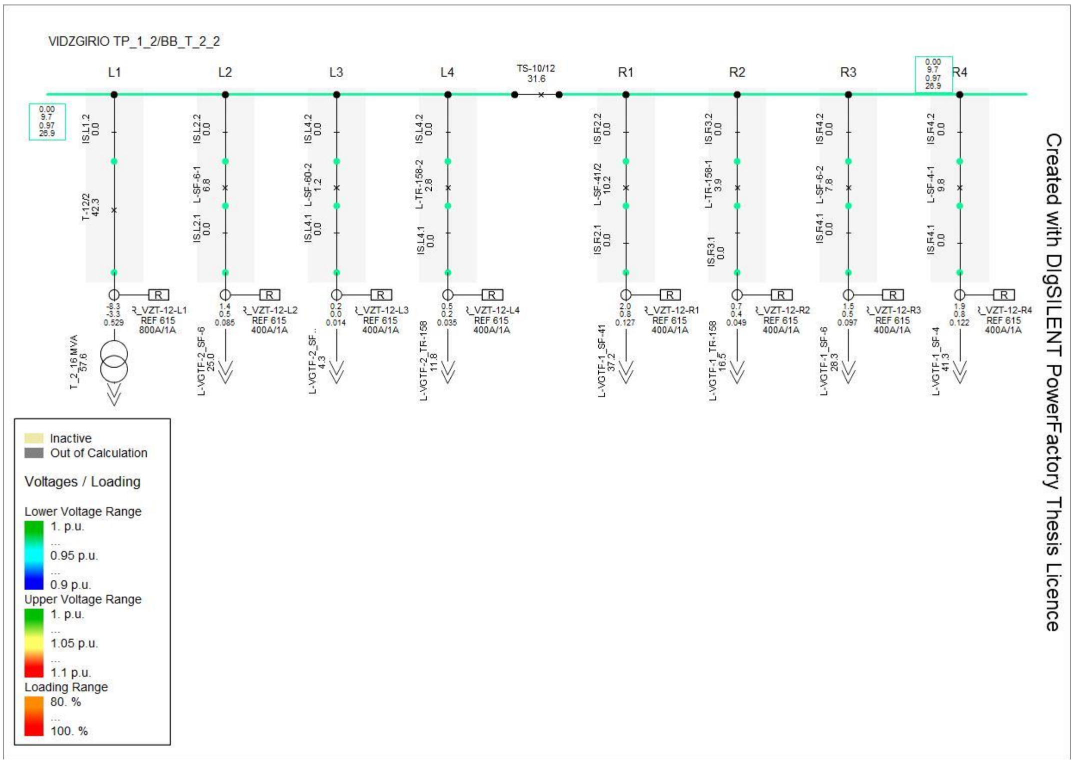


Fig. Load flow results for VIDZIGIRIO TP Bus 1 and 2 buses

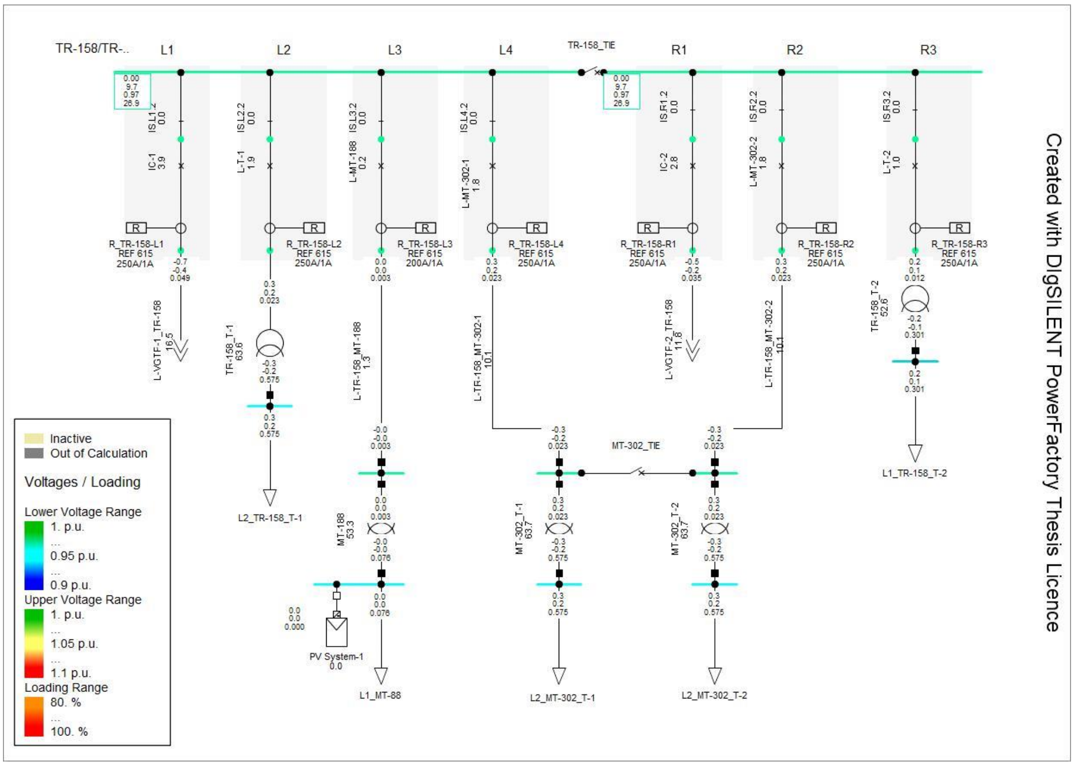


Fig. Load flow results for TR-158 substation

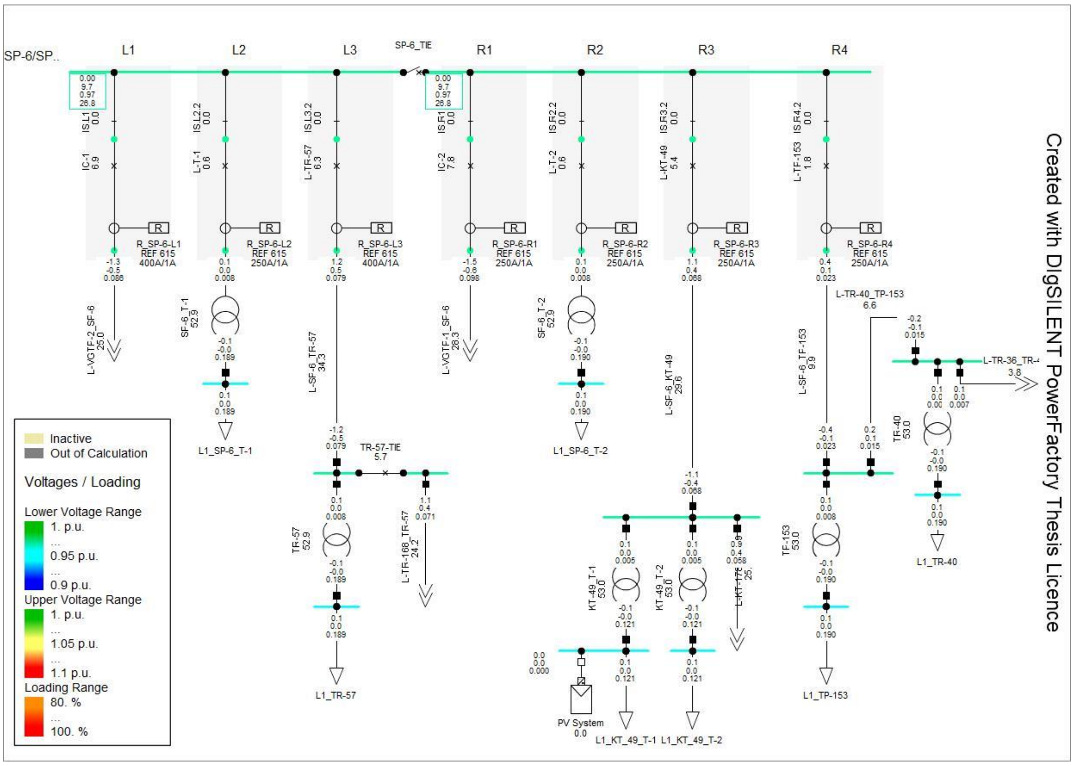


Fig. Load flow results for SP-6 substation