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Design and Evaluation of Electrical Protection for Grid-Connected Microgrid with Renewable Energy Resources

Dr.Shailesh Madhavrao Deshmukh[1], Charpe Prasanjeet Prabhakar[2]

[1]Assistant Professor, Department of Electrical, Kalinga University, Raipur, India.
ku.shaileshmadhavraodeshmukh@kalingauniversity.ac.in

[2]Department Of Electrical And Electronics Engineering, Kalinga University, Raipur, India

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Abstract:

The objective of this article was to establish the dependability of the Over Current protection (OCP) technique in safeguarding microgrids that use inverter connected Renewable Energy Sources (RES) for lower-voltage distribution channels. The simulation program was used to conduct OCP system experiments to demonstrate its dependability. The simulations included contrasting the system's performance in grid-connected mode, both with and without RES production, and in the island state. The calculations are performed with a lower-voltage distributing system design. The average relay tripping time for single line-to-ground (SLG) faults via grid mode, without RES systems, is 0.131 seconds. For line-to-line (LLL) faults, the mean tripping time is 0.121 seconds. Regarding RES generators, the mean relay tripping duration climbed to 0.199 seconds and 0.135 seconds, combining both. This is caused by the fault current generated by the addition of RES production, which limits the current detected by the specified Over-Current (OC) relays. The results indicated that a few Over-current relays failed to activate during the island scenario, resulting in a lack of synchronization and reduced fault currents. In the island scenario, the system underwent further testing at various generation ranges (15%, 50%, and 80%), revealing a slight disparity in mean tripping time across different generation stages.

Keywords: Microgrid, Renewable Energy Resources, Electrical Protection, Electrical grid.

1. Overview of the research

Renewable energy has become more critical in power networks in both emerging and rising nations. This shift from a minor factor to a major one is primarily attributed to the expected significant role that renewable energy will play in achieving the goals outlined in the Paris Accord. The United Nations Framework Convention on Climate Change (UNFCCC) established a goal of achieving a 20 percent adoption rate of clean energy in the electricity sector by 2022 in Paris [1]. The widespread use of Renewable Energy Sources (RES) drivesthe need for global power system changes [2].A novel personalized services architecture for HEMS service providers is presented in this article [3].

Implementing wind and solar units makes it feasible to provide sustainable electricity to small-scale systems within well-specified limits. However, the conventional safety measures of these microgrids are compromised due to the specific properties of short-circuits [22]. The intermittent impact of Distributed Units (DG) and local demands affect the bi-directionality of electricity flow [4]. In addition, DGs further exacerbate short circuits, even when they are not immediately implicated in the failure. Moreover, modifications in the microgrid configuration and how it operates, such as being connected to the primary power grid or functioning independently, pose a risk to the predetermined configurations [5].

RES integration alters the network configurations and results in varying and sporadic fault levels. These modifications challenge pre-established safety measures since they fail to function when necessary. Therefore, developing novel protection techniques or adapting the current protection strategies is essential to effectively manage and regulate power networks that include Renewable Energy Sources (RES) [6]. Extensive studies have been conducted on safeguarding sub-transmission systems with RES cooperation since wind power is often linked at this stage. Nevertheless, the use of solar energy in distribution lines is growing. However, there is a need for more research publications that specifically address the safeguarding of these networks. More research is needed on safeguarding 0.4 kV distribution systems with inverter-linked RES, especially when the microgrid transitions between different operating modes [7]. The studyprimarily focuses on the safeguarding of 11 kV distribution systems. This researchaddresses the gaps by examining various protection mechanisms for 0.4 kV distribution systems with inverter-linked RES. It seeks to suggest a safety method that offers reliable safeguards in both operating modes.

It is important to emphasize that all proposed differential protection techniques need a Current Transformer (CT) at each line termination and another in the DG feeders [8]. In contrast, traditional radial grids employ a single CT and a circuit interrupter in every transmission line to provide coordinated protection against overcurrent. However, renewable sources do not make this method more appropriate because of fluctuating short-circuit values. This study introduces a straightforward method to construct the conventional differential current component using fewer CTs. This technique is further supported by an incrementally current-based technique to prevent malfunctioning in standard distribution systems. In addition, a backup safety mechanism is used to ensure the complete removal of faults in areas with no signal coverage [9,10]. The microgrid's ability to function well in many settings, both when connected to the primary power grid and when operating independently, using either a radially or ring structure, makes it a viable option for protecting the microgrid.Fuzzy clustering and fuzzy Naïve Bayes models are used for intrusion detection in the proposed approach, which employs an Ensemble optimization technique to tackle network security challenges via the efficient utilization of the energy component [11].

The following sections are organized in the specified sequence: Section 2 examines the electrical protection mechanism used in microgrids. Section 3 discusses the proposed electrical protection system and its mathematical model. Section 4 explores the process of software analysis and presents its results. Section 5 summarizes the study by showing the conclusion and results.A novel algorithm called Simple Globally-Energy-Aware Migration (SGEAM) is introduced this article [23].

2. Literature Analysis

The differential safety feature is extensively used in commercial electrical and communication network switches. This notion continues to serve as inspiration for developing novel relaying methods. For instance, Wang et al. suggested using differential safety as a secondary safeguard in a microgrid, which is to be activated if there is a failure to coordinate the current overload and directional preventive components [25]. The preventative method proposed by Li et al. incorporates a differential component for high-risk areas and a flexible low transmission load approach for less threatening situations [12]. However, Adewoleet al. introduced a new method of current intensity differential safeguarding for active distribution systems, considering the impact of inductive motors on the power supply [13].

As Mehmoodet al. proposed,the differential resistivity idea is used to coordinate the safety of supplies in a radial microgrid [14]. Guptaet al. utilized the differential resistance slope [15]. A divergent frequency-based variable was derived from the finding that the frequency elements of the electricity recorded at both ends of a distributing line exhibit disparities in the event of a short circuit. In addition, the interharmonic elements have been employed for a differential purpose [16].

The new concept addresses the issue of temporal synchronization inaccuracy in differential safeguarding by automatically defining the current limit and considering the electricity magnitude proportion on both endpoint CTs. Li et al. used stacked voltage and present data to develop a differential energy relaying technique [17].

Wang et al. propose a multi-agent safeguarding strategy that utilizes divergent function coordination and fault clearance time [18]. Ju et al. utilized a multi-agent technique that consisted of a rapid online method and an offline safeguarding component [19]. Using an alternative method, a differential component was created using local fault identification by contrasting the binary state outcomes of relays located at each terminus of the transmission lines. Bekhradianet al. utilized the active power distinction idea with Phasor Measuring Units (PMU) [20].A resilient technique that uses variational inference to estimate the variation in neural network posterior weights minimizes the divergence between the prior and actual distributions of the network's posteriors. This design, called SGtechNet, maximizes the detection accuracy of invariants [24].

3. Electrical protection system for microgrid

A microgrid is a self-sufficient and manageable power system comprising DG, controlling devices, energy storage, and demand. A microgrid is a compact electric power system encompassing generation, transmission, and dissemination. It can achieve the most efficient energy distribution and maintain a balanced power level within a designated region. A Micro-Grid (MG) is more flexible than traditional electricity transmission and distribution grids. The energy storage system and the dispersed supply are directly linked concurrently to the demand. A microgrid's autonomous administration, control, and safeguarding capacity enables it to function in grid-connected and islanded modes.

When an MG is linked to the grid, it connects with the electricity network via a Point of Common Coupling (PCC). It engages in electrical exchange with the transmittingor sub-transmission infrastructure of the power network. Whenever an MG is islanded, it is disconnected from the power supply. In a significant disruption, the grid supply is cut, allowing the microgrid to run autonomously in off-grid or island status. Meanwhile, the distributed generators will continue providing power to local loads. Yet it is possible to link it to the power grid when the amount of electricity generated is insufficient to fulfill the demand.

A Direct Current (DC) to DC converter links distributed generators, battery energy storage systems, and DC demands to a DC bus in a DC-MG system. An inverter connects the Alternating Current (AC) loads and the DC bus. The primary benefit of the DC-MG is its ease of control, whereas the primary drawback is the need for inverters to provide power to AC loads. An AC-MG distribution system is directly linked to an AC bus. AC microgrids are mostly prevalent since they eliminate the requirement for convertersto deliver electricity to AC loads. The primary drawback lies in the complexity of operation and management. A combination MG, consisting of a DC bus and an AC bus, is being developed. The DC bus efficiently delivers power to DC demands, though an AC bus instantly supplies power to AC loads, as seen in Figure 1.

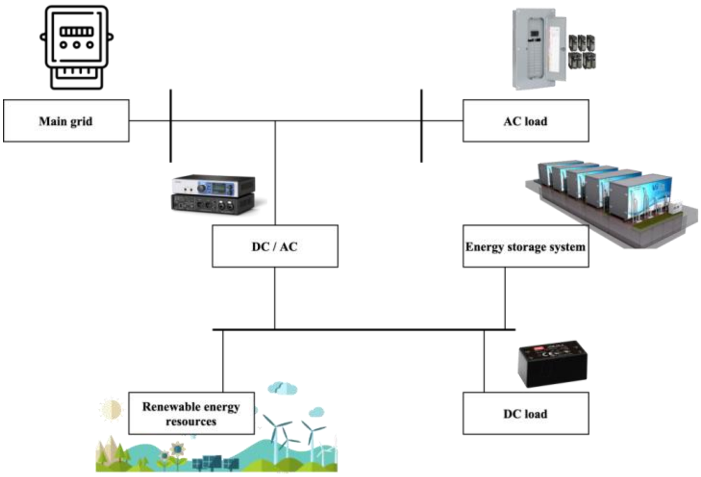

Figure 1. Proposed microgrid system with electrical protection

3.1 Energy storage systems

The techniques are offered to address the imbalance between supplies and demands because of the unpredictability, reliance on sunlight, and intermittent DGbehavior. RES is contingent upon the presence of solar light, while electricity is required continuously. Thus, solar power plants must incorporate energy storage devices to offer electricity around the clock. Connecting a converter to provide electricity to AC demands is also necessary. The energy system serves several functions: control, equilibrium, black start capability, and power quality modification. The energy storage technology has several forms, including natural, electrochemical, and electromagnetic. The tangible manifestations of energy storage technology include flywheel, pressurized air, and pumped storage. The electrochemicalenergy storage technology variant encompasses many capacitors. The electromagnetic energy storage methods include several categories of capacitors. Controllers for charging often come with the installation of the energy storage system. A charge controller's primary function is disconnecting the demand when the battery's discharge condition becomes undesired. It must also disconnect the solar panel array supplies when the battery energy storage system is wholly charged.

3.2 Protection and communication

Switchgear isequipment that switches, regulates, and safeguards electrical systems and devices. Switchgear gear comprises switches, Circuit Breakers (CBs), fuse boxes, and relays. A relay is an apparatus that identifies a malfunctioning situation and transmits a signal to activate the circuit breakers. A conventional relay circuit comprises a Current Transformer (CT) with an initial winding linked in series with the device requiring protection. The additional winding of the CT is connected to the operational coil of the relay. If a defect occurs, there is an increase in current flowing through the primary circuit, resulting in an elevation of the auxiliary electromotive force. Supplying power to the relay working coil activates and then transmits trip signals to the circuit breaker's operating coil, contingent upon the delay parameters. The initial activation of the circuit breaker prolongs the relay's functioning duration. Various kinds of circuit breakers have distinct operational durations. Generally, a low voltage circuit breaker is expected to function within 1 to 3 cycles, which corresponds to 10 ms to 50 ms in a 60 Hz circuit. The predicted operating time for an average voltage CB is 50 ms to 200 ms for a 60 Hz structure, corresponding to 2 to 6 rounds.

3.3 Protection logic description

At this location, there is a connection between two distribution cables, DL-1 and DL-2, at a shared busbar. A load, L-2, is assigned to this busbar. In addition, a distributed generating unit, DG-1, provides power to the load L-1. The alternating current transformers CT-1 and CT-2 are positioned at the start of DL-1 and DL-2, accessible via the circuit breaking pairs CB-1–CB-2 and CB-3–CB-4, accordingly. In addition, DG-1 is equipped with its current converter, or CT-DG-1, and a circuit breaker known as CB-DG-1.

Contrary to the standard differential system, the CT frequently employed on the right side of DL-1 is absent. However, CT-2 is usedinstead. The process and restraining currents are computed as follows:

$$I_{op} = |I_{CT-1} - I_{CT-2} + I_{CT-DG-1}| \quad (1)$$

$$I_{res} = |I_{CT-1}| + |I_{CT-2}| + |I_{CT=DG-1}| \quad (2)$$

If the criteria of Equation (2) are met, the trip signal is issued to the circuit breakers CB-1, CB-2, and CB-DG-1 according to these computations. If the shown architecture is used, DG1 will continue to provide power to load L-1. Conversely, the circuit switches CB-3 and CB-4 stay closed, ensuring that the load L-2 receives power from downstream sources.

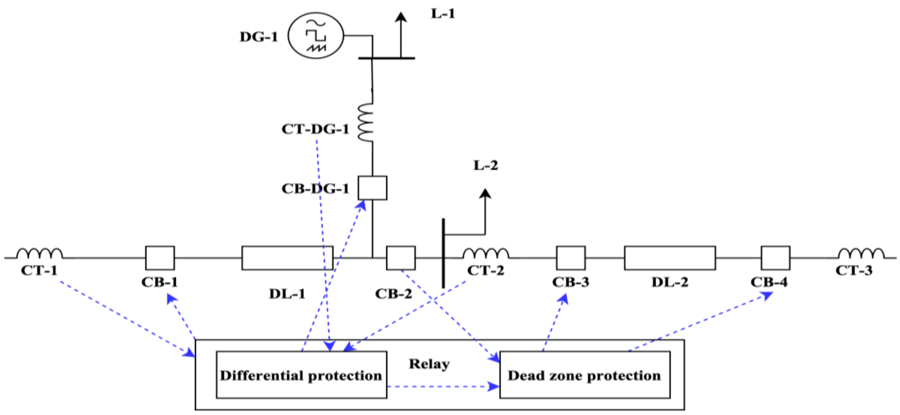

Figure 2. Electrical protection system with circuit breaker

However, activating these circuit breakers will resolve the fault inside the designated protected zone of DL-1, which is defined by these circuit breakers, such as the fault F-1 shown in Figure 2. Furthermore, detecting the presence of a dead area, such as the one between CB-2 and CT-2, is feasible. Therefore, complementary logic is required to address this problem and rectify fault F-2. This supplementary feature uses the logical condition of the opened circuit breakers as inputs and ascertains if the trip criteria of the differentiable functions are still met in zone 1. The result generated by this backup component is a directive to initiate a journey for CB-3 and CB-4.

3.3.1 Main protection logic description

Firstly, it is confirmed that the inside fault criteria specified in Equation (2) of the divergent component are met: the logic status of S_{IF}= 1. Typically, these requirements must be completed within a quarter phase, which is the shortest time for CT coverage. The involvement of DGs in areas with good health conditions might enhance the awareness and importance of protecting such areas. To improve the safety of the whole microgrid transmitting system, implementing an additional operational current, ΔI_{op}, in every protected zone is crucial. This measure effectively prevents mistakes in operation and is computed as follows:

$$\Delta I_{op} = I_{op}(x) - I_{op}(x - M) \quad (3)$$

In order to activate the relay, the difference in current, ΔI_{op}, must exceed a specified minimum value, ΔI_{min}. A proportion is computed between the change in I_{op} for the areas where S_{IF} equals 1. It is confirmed that the index of the faulty zone is at least $\lambda\Delta I_{op}$ times more than the other zones. The trip signal is transmitted to CBs when the requirements of both the divergent and sequential components are met.

A supplementary approach was implemented to dynamically determine the most miniature pick-up to handle production and load fluctuations effectively. This straightforward logic requires two inputs: the action's current and its associated simultaneous progressive value, which is computed as

$$\Delta I_{op-x} = \frac{|I_{op}(x) - I_{op}(x - M)|}{\Delta t} \quad (4)$$

It is important to note that ΔI_{op-x} is distinct from the progressive operating currents, ΔI_{op}, that are employed to identify non-faulted safety areas. The latter are computed with a one-cycle gap between sampling. From this, it can be inferred that the minimal pick-up should be M times the operational current when there are changes in load or generating outputs. This determined if ΔI_{op-x} is less than a specified minimal value. When a short-circuit happens, the value of I_{op-min} suddenly rises. It should then take on the value from one cycle when the error occurred and maintain it.

3.3.2 Backup dead zone protection logic

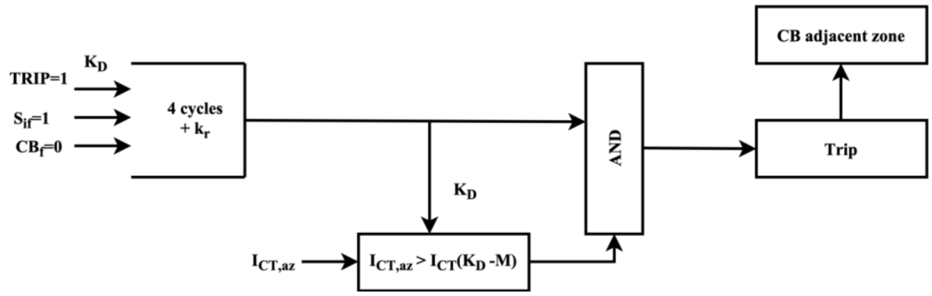

Figure 3. Logic diagram for the dead area protection

As shown in Figure 3, the depicted logic determines the exact moment, denoted as k_r, when the message TRIP was transmitted to the breaker panels in the zone experiencing a problem. The status of the internal fault is consistently confirmed, specifically denoted as S_{IF} = 1. Again, the operational state of the opened circuit breakers in the affected area is also seen, denoted as CB = 0. If these circumstances persist for four cycles following the moment k_r, activating the circuit breakers in the next zone where a power source is causing the short circuit is necessary. From a technical perspective, the safeguarding area in question includes a current CT used in the first faulty safety zone. However, the current in this CT rises after the circuit breakers are opened. In the mathematical execution, the dead area fault is detected at the moment k_D, which is equal to $k_r$plus four times N. The open neighboring zone relies on the signals from the accurate standard CT,I_{CT-az}, where the currents rise after k_D.

4. Experimental Findings

Tofulfill the objective of this research, a computerized model of a 24.9 kV microgrid was constructed using the EMTP software [21]. The microgrid consists of 4 distributed generators, represented as three-phase voltage source converters, as well as five distributed loads and five regular loads. The safety plan incorporates 11 current transformers with a ratio of 100:5, 16 circuit breakers, and six designated protection areas. The simulated examples pertain to five fault sites occurring during the microgrid operation in both on-grid and off-grid ways for both ring and radial architectures. Many simulations were conducted to determine the operational methods for Distributed Generators to ensure the consistency of voltage and frequency during off-grid operations. DG-1, DG-3, and DG-4 use the voltage-to-force option, while DG-2 stays in the PQ form.

Table 1. Tripping time analysis

Simulation Mode	Fault Type	Tripping Time (s)
Grid without RES	SLG	0.131
Grid without RES	LLL	0.121
Grid with RES	SLG	0.199
Grid with RES	LLL	0.135

Table 1 shows the results of tripping time. When operating in grid mode without RES input, the OCP systems exhibited a tripping duration of 0.131 seconds for SLG faults and 0.121 seconds for LLL faults. IntroducingRES production in grid mode has increased the duration of tripping times.The tripping time for SLG errors is now 0.199 seconds, while for LLL faults, it is 0.135 seconds. The observed correlation between RES production and longer tripping duration is due to the photovoltaic system's introduction of extra fault current. These results highlight the need to include renewable energy sources when building microgrid electrical safeguards.

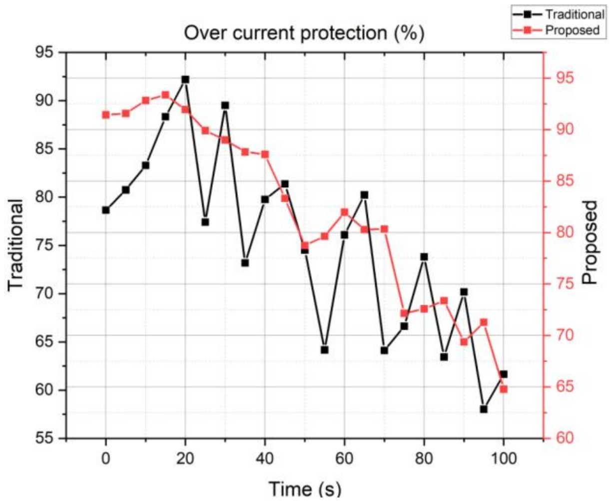

Figure 4. Over-current protection analysis

Figure 4 summarises the current protection analysis of the traditional and proposed methods. The suggested study on over-current protection exhibits a significant performance improvement compared to the conventional approach. At the first moment, the proposed approach attains a protection effectiveness of 99.2%, exceeding the 98.5% effectiveness achieved by the previous method. The suggested solution constantly surpasses other methods over the whole duration, ranging from 0s to 100s, demonstrating its superiority in sustaining greater protective effectiveness. The study that considers the passage of time reflects the efficiency of the proposed strategy to provide more excellent safety compared to the present method. This aligns with the study's goals.

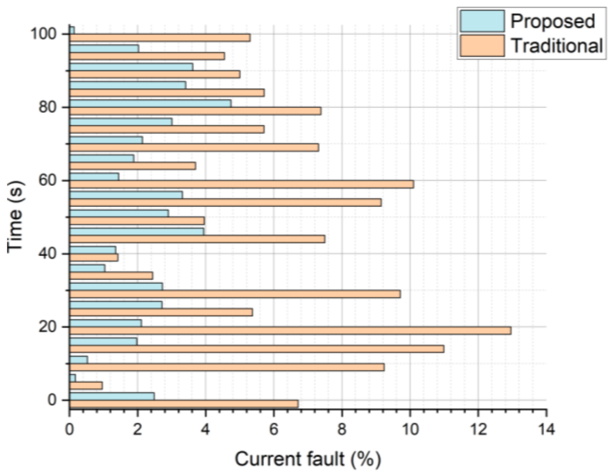

Figure 5. Current fault analysis

The current fault analysis of the traditional and proposed method is shown in Figure 5. The research study on Current Fault demonstrates a significant improvement in fault mitigation when using the suggested strategy in contrast to the conventional methodology. At the first moment, the traditional approach begins with a somewhat high fault percentage of 6.71%, while the suggested approach attains a substantially lower value of 2.49%. Over time, the proposed approach continually improves performance by maintaining lower electrical fault percentages over the simulation length. The decrease in electrical fault rates provides evidence for the suggested strategy's effectiveness in improving the electrical infrastructure's dependability and consistency, which aligns with the study's goals.

5. Conclusion and Discussion

Most renewable energy sources are anticipated to be integrated into the electrical grid. This suggests that there will likely be a shift from centralized generation to distributed generators and microgrids. There is a need to identify innovative methods for efficiently safeguarding MGs. Microgrids equipped with inverter-interfaced RES production need adapted protection strategies that effectively protect the MG during both islanded and grid-connected states because of the disparity in I_f levels seen in these two modes of operations. Differential electrical relays can effectively address safeguarding difficulties associated with I_f stage fluctuations and bi-directional electric power.

- The simulations were performed on a lower-voltage distributing network configuration. The analysis of OCP has been conducted in both grid-connected and non-grid-connected scenarios. The first point isthat the mean relay tripping time for single line-to-ground failures in grid mode without RES systems is 0.131 seconds. However, for line-to-line errors, the mean tripping duration is 0.121 seconds.
- The mean relay tripping duration rose to 0.199 seconds and 0.135 seconds, combining both, due to the connection of RES generators.
- IncorporatingRES production in the system limitsthe current observed by the configured OC relays.
- Due to a drop in collaboration and a fall in I_f, a small number of OC relays failed to trip during the islanded function.
- The system underwent further testing at various generation levels (15%, 50%, and 80%) while operating in island status. The results showed a slight disparity in mean tripping duration across various generation rates.
- The findings underscored the constraints of inverse time overcurrent relay safety.

Evidence suggests that the inverse time overcurrent relay safeguard is susceptible to alterations in short circuit levels. In addition, it is being shown that relay cooperation becomes impaired while transitioning from a grid-connected state to an islanding state.

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