Machine Learning Techniques For Optimal Power System Protection: A Review

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***Abstract*—The reliability and resilience of the power system from generation, transmission and distribution value chain depends on the efficient operation of the protection system. Several approaches have been invented by engineers and scientists to optimally protect the electricity network to reduce downtime as a result of faults. The advent of Artificial intelligence and the machine learning techniques such as the have afforded the power protection engineers a novel opportunity to improve the reliability of the electricity network, increase availability and ultimate make the electricity network safe and efficient. Support Vector machine technique, K-nearest neighbours, Artificial neural network, Decision tree, Random forest techniques, etc., for fault detection, classification, feature extraction and location of faults in the transmission network has been utilized, hybrid system includes the combination of two or more machine learning techniques to design algorithms built into a model for power system protection purposes. The paper review indicates successes so far achieve in reducing system collapse and improving availability in our electricity network.**

Keywords— Power System Protection, Artificial Intelligence, Machine Learning Techniques

1.0 Introduction

In the recent time, there has been frequent reoccurrence of system collapse of the grid network (Aibangbe and Eyenubo, 2017) in Nigeria an in several parts of the world, that have given room for much to be worried about the electricity supply network. According to Jerimiah, 2022, the resilience of the grid network is contributory by the players in the value chain including generation, transmission and distribution and there have been many investments in the construction and re-enforcement of the high voltage network to ensure optimal operation, efficiency and reliability.

There is an increased demand for electric power system and the de-regulation in various climes predicts lots energy utility stress, leading to power system and control issues, and the ability of power system engineers to provide uninterrupted, dependable services in the face of cascading outages is critical to the performance of the electric power system security where load should be fed with quality electricity supply, that is of optimal power quality (PQ) (Sonwani and Rathore, 2021), which includes voltage and system frequency of the supply (Ntambara and Umuhoza, 2022).

In the research by Raza *et al*. 2022, electricity supply is disrupted when unplanned disturbances appear in the power system network, the effect impacts negatively and outrageously on the economics, social, and political aspect of human life. These breakdowns have negative consequence for the various sectors, including educational, medical, testing laboratories, industries, water supply pumps, banks, small and large business centres, and almost every walk of life, creating a huge toll on social, political, and economic activities, which at times are irreversible.

Industries are dependent on electricity; manufacturing and production work is affected very badly due to the absence of electricity as dependent on diesel generators by industries lead to the soaring of price of products (Raza *et al*. 2022). The resilience of the power system network is largely connected to the performance of the power protection system, these includes achieving the proper coordination of the protection system that needs to be evaluated for reliability, Sabzebin *et al*. 2022, acknowledged this when they stated in their paper that the operation of the protection system has a considerable effect on the reliability of the power system, also that the failure of the protection system results in loss of load and imposed a blackout in the system. According to Rehman *et al.* 2022, electrical power system is a highly invested area which requires adequate protection to keep faulty section of the network disconnected from the healthy section, thus minimizing disturbances and maximizing connectivity by creating a zone of protection on the engineering design of the protection relay scheme employed.

Already there is extreme electricity shortage in the power system network occasioned by poor infrastructure, according to Dickson, *et al*. 2023, dilapidation in the electricity network due to lack of modernization and infrastructural improvements, lead to electricity poverty, the inadequacy could be addressed by augmentation of the power system distribution network using distributed generation (DG) embedded in the existing network, where the paper converged in support of the idea of DG embedded in the distribution network, there must also be adequate protection of the DG both in island mode and on interconnection mode. Also currently, smart grid arrangement entails DGs being interconnected to the grid network and many algorithm for power flow of distribution system with high penetrating DG have been developed (Musa, 2015), and categorized as Node based and Branch based method used as state variables. Node based used current or voltage injection as state variable for solving power flow problem, and includes, network equivalent method, Z-bus method Newton-Raphson and Fast decouple algorithm, whereas, the Branch based method includes the use of branch current or power as state variable for the power flow solution (Musa, 2015).

Raza *et al*. 2022 identifies various causes of power system collapse to include bad weather condition, human error, faulty equipments, overloading, and proffered solution to include the application of modern control and protection system as ways of mitigating the menace of power system blackout and its effect on the economic development of any country. Therefore even when the installed capacity of a country's power generation stood at about 12,000MW of electricity, for instance, (Joseph, 2014) and including weak transmission and distribution infrastructure, effort must be put in place to improve the stability of the system by employing adequate protection scheme to achieve the goal of providing stable and reliable electricity to the consumers.

As at today many countries of the world practice the radial distribution network. The disadvantage is that a fault in a portion of the network would lead to a total shutdown of that entire network of feeders. Chinwuko *et al*. 2011, researched on the technical issues affecting power generation and distribution and emphasized on effort that should be made towards sustainability of power system network, the distribution system being the tail end of the value chain and adopting the interconnected distribution network would allow for continuous supply of electricity to other consumers while a portion of the network is on outage thus reducing the frequency and duration of outage and blackout in the electricity supply (Raza *et al.* 2022).

The interconnection of the power system network was to augment the capacity, (Dickson, *et al*. 2023, Khair *et al*. 2018), to accommodate loading and increase resilience and stability of the system, to accomplish these, a smart grid utilizing modern electronic sensors, communication links, and computational power system protection to improve efficiency, stability, and flexibility of the system was introduced, and the three primary function of the protection system includes first, real-time monitoring and reaction, which allows the system to constantly tune itself to an optimal state (Ma, 2021), secondly, anticipation which enables the system to automatically look for problems that could trigger larger disturbances, thirdly, rapid isolation which allows the system to isolate parts of network that experience the failure from the rest of the system to avoid the spread of disruption and enables a more rapid restoration.

To improve the efficiency of the protection system, wide area monitoring (WAN) has been developed and applied (Wang, 2021, Khair et al., 2018) where Phasor measuring units (PMU) are applied alongside Phasor data concentrators (PDC) used for data collection, data forwarding, data processing, data analytics and data storage functions. In this case, the PMU work with the PDC to improve data mining, (Alassaf, 2021and Lu *et al*., 2023).

Several approaches have been researched over the years seeking to improve the efficiency of the protection system, Bo *et al*. 2016, discussed the elementary principle of power system protection which started from the electromechanical over-current, directional, distance and differential protection as protection principles developed in the last three decades. To improve the performance of power system protection, wide area monitoring (WAM) system was developed, (Phadke *et al.,* 2016, Habib *et al*., 2023). WAM includes monitoring the suitability of the relay characteristics, supervisory control of backup protection, more adaptive and intelligent system protection scheme. In adaptive relaying, the relay settings and relay pickup currents could be changed in an online mode as operating condition of the system changes (Kocaman and Akca, 2019), thus the protection system adapts to different operating condition and offers more selective and reliable protection when compared to the conventional protection system.

The challenge of constant fault and isolation of several feeders in the network has not been fully resolved hitherto, adaptive protection scheme with auto reclose have been experimented on the micro-grid network (Sitharthan *et al*. 2016) leading to a quick recovery of the system from fault condition. The outstanding principle of this adaptive protection scheme is that it monitors the micro-grid and instantly updates relay fault current according to the variations that occur in the system, thus system recovers faster from fault and the consistency of the system is increased tremendously.

The protection system is categorized by protection zones which are defined by the equipment and the isolating circuit breakers, according to Kocaman and Akca, 2019, there are six categories of these protection zones, namely; generator and generator-transformer unit, transformer, buses, line (transmission, sub-transmission, and distribution), utilization equipment (motors, static loads, and others) and capacitor or reactor banks, if they are separately protected. The fundamental protection principles are quite similar though, but each of the six categories of zones has protection relays which are specifically designed for primary protection. These are often based on the characteristics of the equipment to be protected (Rehman, 2022).

The correct operation of the protection relays depends on the proper setting of the protection relays, as well as the protection components being healthy (Sabzebin *et al.* 2022). Incorrect settings of the relays could results in the miscoordination between primary and backup relays in the case where there is a fault, leading to the backup protection operating before the primary protection, thus making the healthy part of the network to experience outage and loss of load and in such situation, a larger part of the electricity network could experience blackout due to this miscoordination of the protection system (Sabzebin *et al.* 2022).

The introduction of digital relaying, which includes micro-processors and central computers is a welcome development where micro-computers or microprocessors are dedicated to the individual relaying task leading to the ultra high speed fault clearance (Slatem, 2021). This approach is economical, with improved performance and better reliability thus improving the optimal operations of the power system protection.

2.0 REVIEW OF RELATED LITERATURE

2.1 Power system protection

The purpose of a protection system is to clear the fault occurring in a power system network so as to ensure uninterrupted supply to healthy network and isolating the supply to faulty network, thus preventing cascading of faulty to healthy circuits leading to system collapse and power system blackout (Tsimtsios, 2020).

Nature and causes of electricity network fault varies and could be from failure of insulation, broken or falling transmission line, incorrect operation of circuit breakers, short circuit or open circuit faults, lightening strike could momentarily increase the voltage to a much higher level, storm could cause mechanical damage, when it blows down pylons, fall trees on the transmission lines, severe snow could cause short circuit of power lines, all of these leads to fault that could lead to the operation of the protection systems in place to protect damage to the system and damage to lives and properties (Tsotsopolous et al., 2023 and Nasser, 2017).

2.1.1 Supervisory control and data acquisition (SCADA)

According to Faryal et al., 2021, Protection of the electric power system is an essential trait in a huge network to efficiently detect and isolate the sections undergoing faults or behaving abnormally. The protection system has components like circuit breakers, fuses, switchgears and relays which communicates from one station to another to ensure high-speed tripping in the event of faults. To automate this system, SCADA along with programmable logic controller (PLC) is employed (Janssen et al., 2019), the purpose is to improve intelligent decision making, sensing, actuating, monitoring and maintaining the record in the host server. Yaday and Paul, 2021, further elucidate this important episode by reviewing the architecture for the SCADA as one way of securing power system termed as critical infrastructure. SCADA can control and monitor geographically distributed assets and power system is one of such. According to researchers like Yaday and Paul, 2021, Das et al., 2017 Aminifar et al., 2021, SCADA system improves the efficiency of operation of the industrial critical system, as well as provides better protection of the utilized equipments using a framework that provide valid identification, prompt alert warnings to the observed stations, using attested monitoring stages, advanced communication and state-of-the-art sensors. Lin et al., 2019 and Vazquez-Gonzalez et al., 2018 agreed with the inclusion of automation and control in the future of the power system protection. Thus with the evolution of Industrial Internet of things (IIoT), modern SCADA system have adopted Cyber-physical system (CPS) / Internet of things (IoT), cloud technology, big data analytics, Artificial intelligence (AI), and machine learning (ML). As a result of the integration of these technologies, significant improvement has been noticed in the area of interoperability of the power system protection system, provides ease of maintenance and a near real-time environment. With this novel approach, complex system could be connected to the internet using advanced technology.

2.1.2 Wide area monitoring

Due to the dynamic nature of power system, it becomes imperative to constantly monitor the power system network to uncover changes in the system that could led to system collapse, wide area monitoring therefore was adopted in the early 80’s and late 90’s for the protection of the transmission, distribution and the generation substations and transmission lines to improve the resilience and reliability of the system. Bo et al., (2016) in his research commented on the milestone achievement on the developments of newer technologies of power system protection including the use of communication technologies and the use of digital techniques where microprocessor-based digital relays replaces the numerical version, subsequently today, more sophisticated technologies as the Artificial intelligence (AI) have emerged such as Artificial Neural Network (ANN), fuzzy logic, and genetic algorithm and have been applied to the field of relay protection.

According to the research done by Palizban, (2015) and Li, (2023), several components and equipments are required to effectively monitor to ensure the reliability of the power system protection and system integrity. One of such components is the Phasor measurement unit (PMU) and Phasor data concentrator (PDC) otherwise called Synchrophasor system which allows the collection and sharing of high-speed, real-time, time-synchronized grid condition data over a wide area of the power system network, thus providing grid operators and system planners unprecedented insight on the events on the network at high resolution in a time synchronized mode over a wide area of the network. This gives rise to the term wide area measurement system (WAMS) (Wang, 2021).

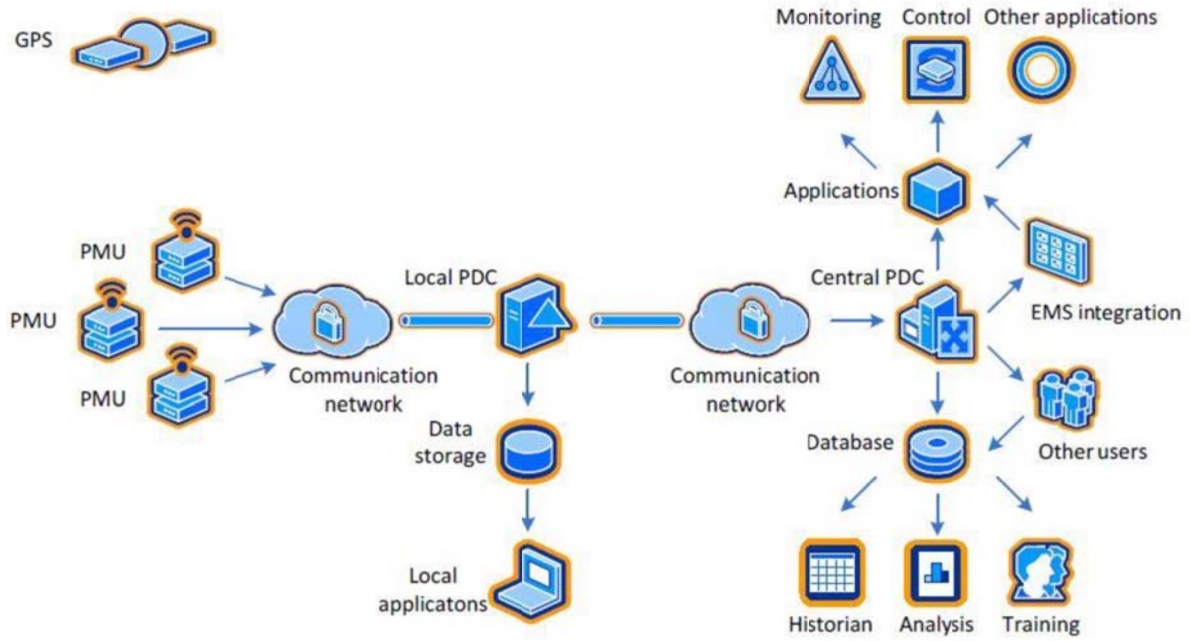

Figure1. Generic Synchrophasor architecture

Source: Palizban, 2015

PMU and PDC are measuring devices, (Khair et al., 2018) that provides highly precision and time-tagged positive sequence Phasor measurement over a widely separated geographical locations of the power system grid network and it accomplishes this task through the production of a synchronized Phasor, frequency, rate of change of frequency estimates from voltage and current signals and a time synchronizing signal. PMU could be referred to as a transducer, it converts or estimate three phase analogue signal from voltage and current into time-synchronized Phasor, it also estimates sequence voltage and current, magnitude and angles, local frequency, local rate of change of frequency, status of circuit breakers and switches, time, location and digital signals

PMU can capture from 8 to 45 signals simultaneously and they are currently incorporated into digital protection relays and fault recorders and are coupled with Global positioning system (GPS) signal for communication and transmission of information and data through internet as shown in figure 1. Figure 2 shows the block diagram of the PMU in connection with other field equipment for effective functionality, while figure 3 shows their placement in the substation.

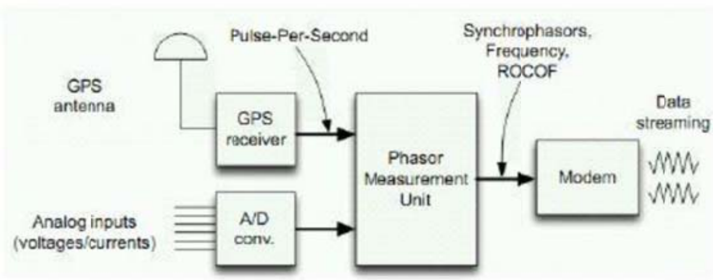

Figure2. PMU functional block diagram
Source: Palizban, 2015

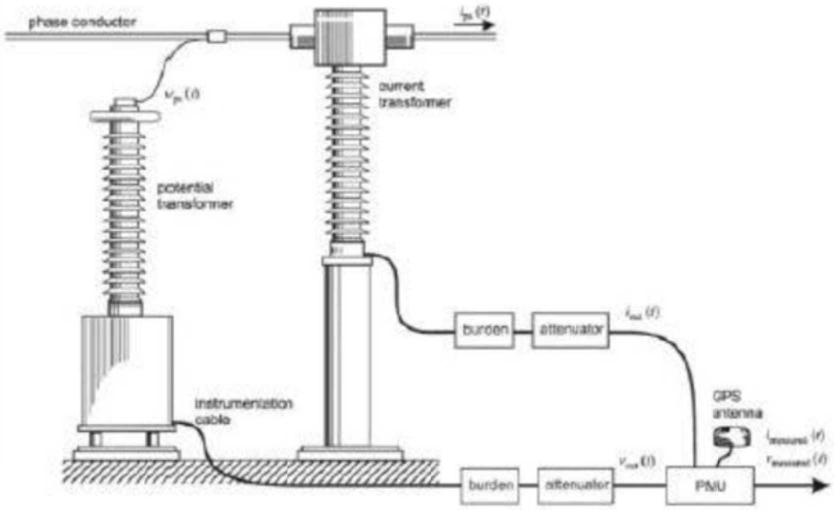

Figure3. PMU devices placement in the substation
Source: Palizban, 2015

According to the wide scale literature review by Palizban, (2015) a broad range of application of PMU in the power system was identified to include, offline and online application listed as follows.

(a) Offline PMU-based application

- Post-Event analysis
- System base-lining and parameterization
- Dynamic model validation
- System protection and control planning

(b) Online PMU-base application

- Enhanced state-estimation
- Situational awareness and visualization
- Oscillation monitoring and control
- Voltage security assessment and control
- Transient security assessment and control
- Frequency stability monitoring and control
- System protection and real-time control
- Transfer capability assessment
- Fault location and detection
- Intelligent island and resynchronization
- Renewable and other application, and discussed the following:

(i). System Base-line and Parameterization

The system base-lining and parameterization enables the determination of the nominal and off-nominal operating condition as it affects the system line parameters, cable thermal ratings adherence, trending path loading and verification of the protection relay settings (Palizban, 2015).

(ii). System Protection and Real-time Control

PMU are also deployed for system protection and control planning, where schemes like the SPS (special protection scheme), SIPS (system integrity protection scheme) and RAS (remedial action scheme) are deployed to enhance planning for special conditions and associated risks. System islanding, generator shedding, load shedding, planned outages and many other techniques may constitute such plans. While conventional protection and control systems primarily consider local measurements or dedicated signal from remote locations, phasor measurements can provide system-wide remote signals, facilitating the development of more advance schemes.

(iii). Enhanced State Estimation

According to Phadke et al., (2016) the speed, accuracy and resolution of the PMU data can significantly enhance the accuracy and convergence characteristics of existing state estimators. PMU data are of higher resolution compared to SCADA based measurements, which provides greater details of the system states. With prudent placement of PMUs, (Wang, 2021) a wider system wide visibility or observability can be achieved which can also be used in ensuring sufficient redundancy in measurement network and estimating the system state more accurately.

(iv). Adaptive protection: According to Sitharthan et al., (2016), adaptive relaying means changing the settings of the protection relays and the relay pick-up currents in an online mode as operating condition of the system changes. Meskin et al., (2023) also defined adaptive protection as an online modification of protection relay settings to address changes in the network by means of external control signals. For over-current relays adaptive protection can be used in two ways, Pre-calculated (Offline) settings and Real-time (online) settings.

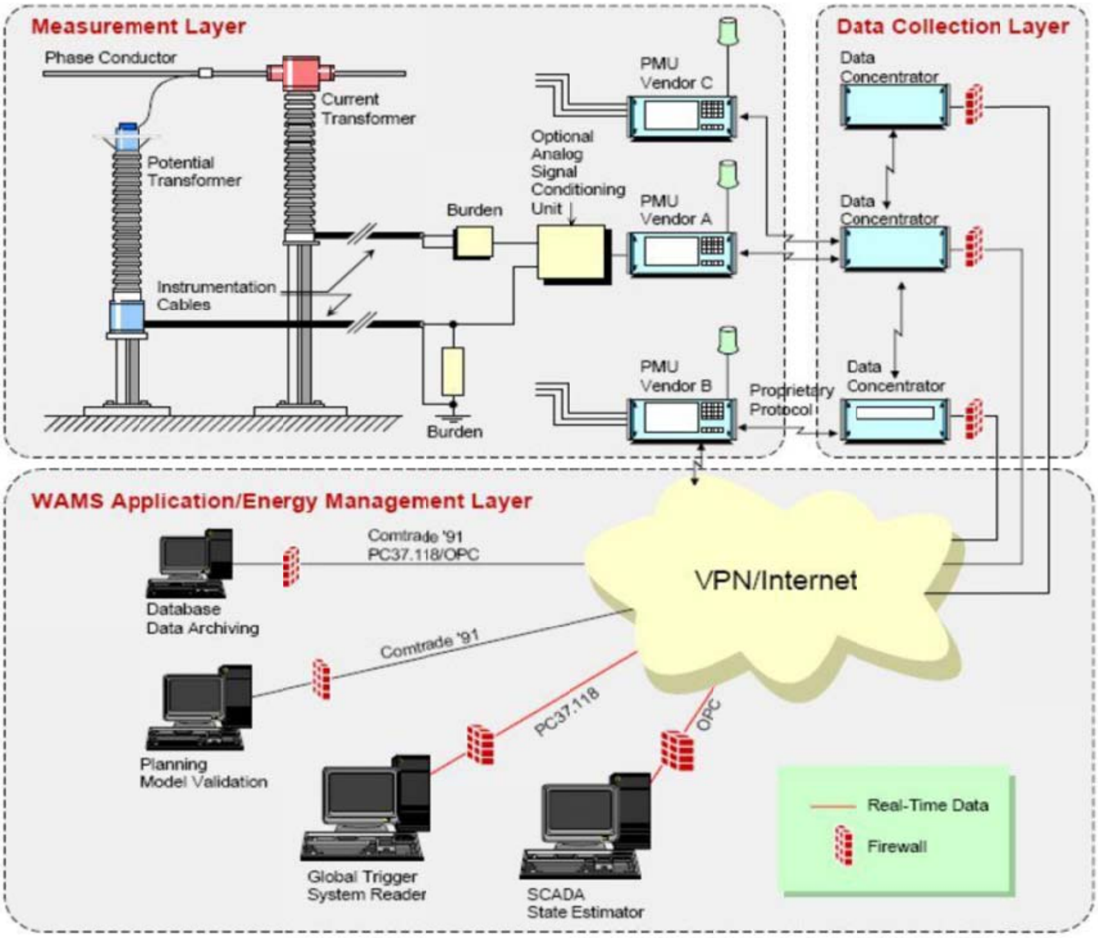

Figure 4. Network overview of PMU

Source: Palizban, 2015.

According to Meskin et al., (2023), in the pre-calculated scenario, settings of different cases are calculated and stored in the relay while eternal signal will activate the appropriate setting. This external signal is generated based on changes in current, voltage and or equipment status, but on the Real-time scenario, the settings of the protective device are calculated and changed online based on the current condition and configuration of the system.

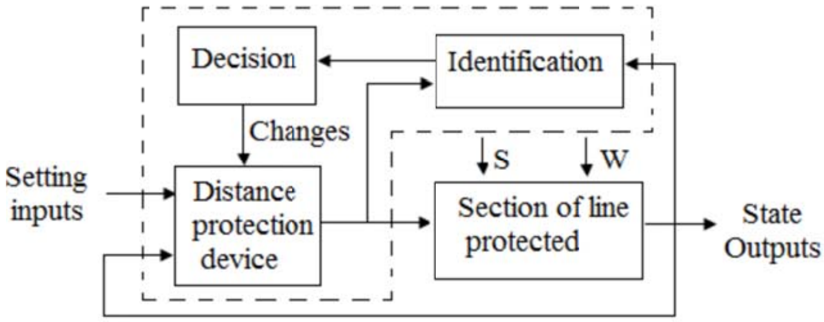

Figure 5. Principle of adaptive relaying

Source: Sitharthan et al., 2016

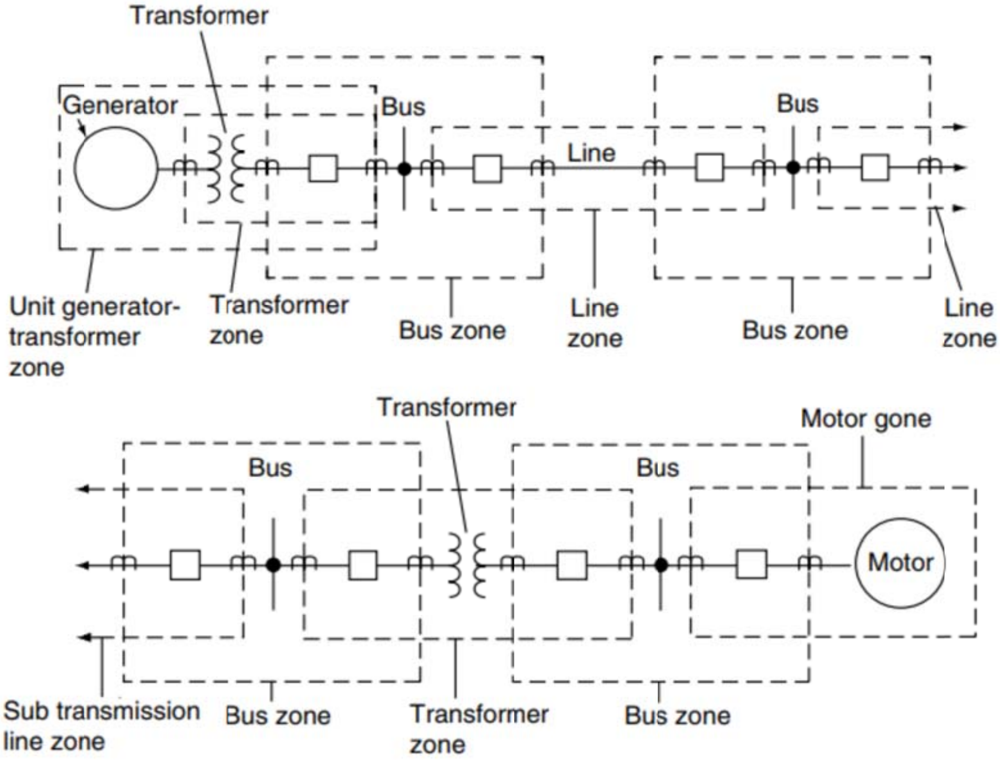

Figure 6. Power system protection zoning

Source: Sitharthan et al., 2016

The principle of adaptive protection scheme is as shown in figure 5, and uses a multi-setting grouping which depends on the protection zone, thus enabling the protection relays to adapt to different operating situations based on the zone of protection as shown in figure 6. Adaptive protection offers more selective and reliable protection of the power system. Adaptive relaying is capable of very high speed operation, maintaining good reach accuracy in the presence of travelling wave noise and is immune to the presence of harmonics or variation in power system frequency.

Application of AI / ML Technology in Power System Protection: Secondary Arc Detection.

There are many areas where Artificial intelligence and machine learning technologies have been applied in power system protection. One of the examples of successful application of machine learning technology was in the detection of secondary arc as discussed by the author.

2.3.4.1 Objective of the Research: According to the author, the problem of secondary arc detection is related to single phase tripping and autoreclosing of a transmission line. Single phase tripping and autoreclosing is used to clear temporary single phase to ground faults, in this case the faulted phase is tripped from both ends of the line and reclosed after a short time of say 1 second (30 -50 cycles). In most cases the fault disappeared within this time and the reclose successful. Single phase tripping refers to the opening of the only faulted phase at both ends of the transmission line thus preventing the flow of current via the faulted line to the fault anymore, and the primary arc extinguished.

Sometimes, according to the author, a secondary arc appears which is fed by the two healthy phases through capacitive coupling as shown in figure14a. The voltage $\underline{\mathbf{U}}_{\mathbf{M}}$ measured at the disconnected phase is characterised by the **ohmic nonlinear behaviour** of the secondary arc termed $\mathbf{R}_{\mathbf{ARC}}$.

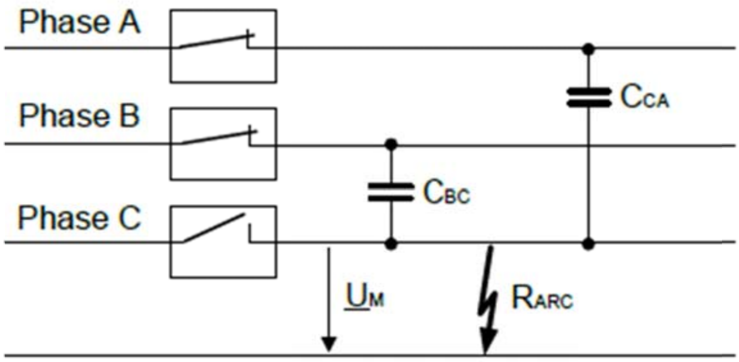

Figure14a: Secondary arc after single phase tripping

Source: Hu et al., 2023

As soon as the secondary arc is extinguished, the equivalent circuit changed to a different model as in figure14b shown below. The voltage **$\underline{U}_M$**, measured at the disconnected phase after the extinguishing the secondary arc is characterised by the linear capacitive behaviour of the phase to ground capacitance **C_{CG}** of the open conductor.

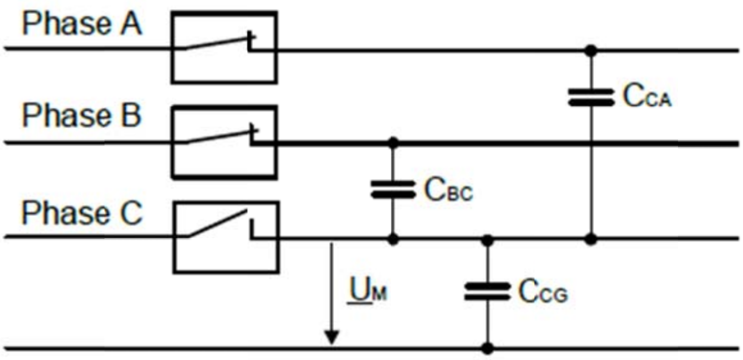

Figure14b: Secondary arc extinction after single phase tripping

Source: Hu et al., 2023

A reclose at presence of the secondary arc was not successful, after the attempt at reclosure, the fault persisted leading to the final tripping of the protection system as shown in figure14c. This unsuccessful reclosure could be prevented using a secondary arc detection function.

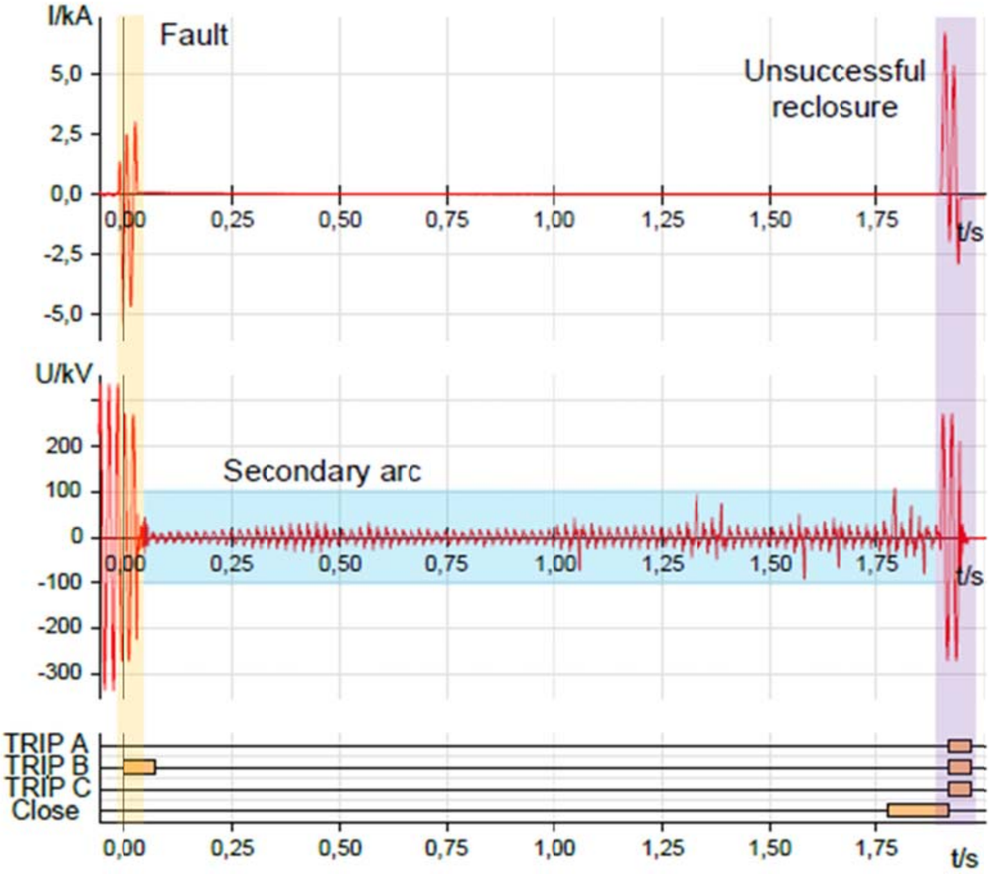

Figure14c: Unsuccessful reclosing when secondary arc is not extinguished after single phase tripping

Source: Hu et al., 2023

A successful reclosure after extinguishing the secondary arc is shown in figure14d, after the line was tripped, the fault current eventually disappeared, at that time the voltage start the typical nonlinear behaviour of arcing, later the secondary arc extinguishes and the voltage kept changing to a linear capacitive behaviour. After successful reclosing, both voltage and current went back to a normal condition. In this case the single phase death time could be reduced from 1.2 seconds to 0.5 seconds, if the extinction of the secondary arc was detected as shown in figure14d.

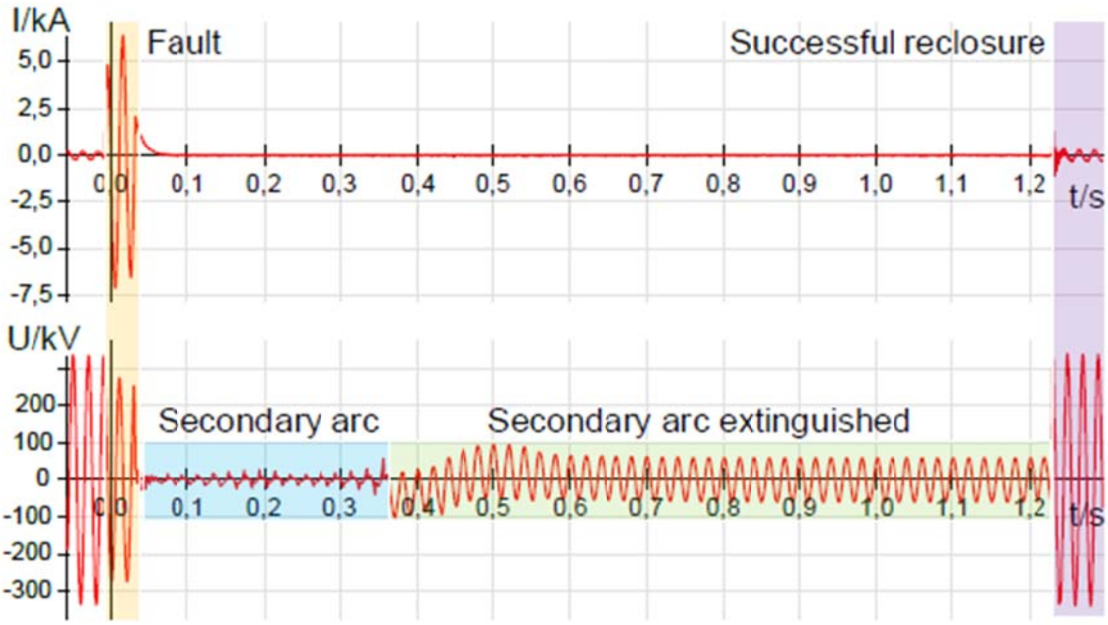

Figure14d: Successful reclosing when secondary arc is extinguished after single phase tripping

Source: Hu et al., 2023

2.3.5 Methodology for implementation: As described by Hu et al., (2023), there are several algorithms that could be used to detect secondary arc based on harmonics or the phase angle of the opened-phase voltage. The algorithm tries to distinguish between ohmic, nonlinear behaviour of the secondary arc and the capacitive behaviour of the voltage if the secondary arc is extinguished. The behaviour of arcing can be different, due to several factors, and according to the author, it was the very reason another algorithm based on Neural Network was added to detect the presence of the secondary arc. The secondary arc detection function uses several criteria to detect the secondary arc as shown in figure14e.

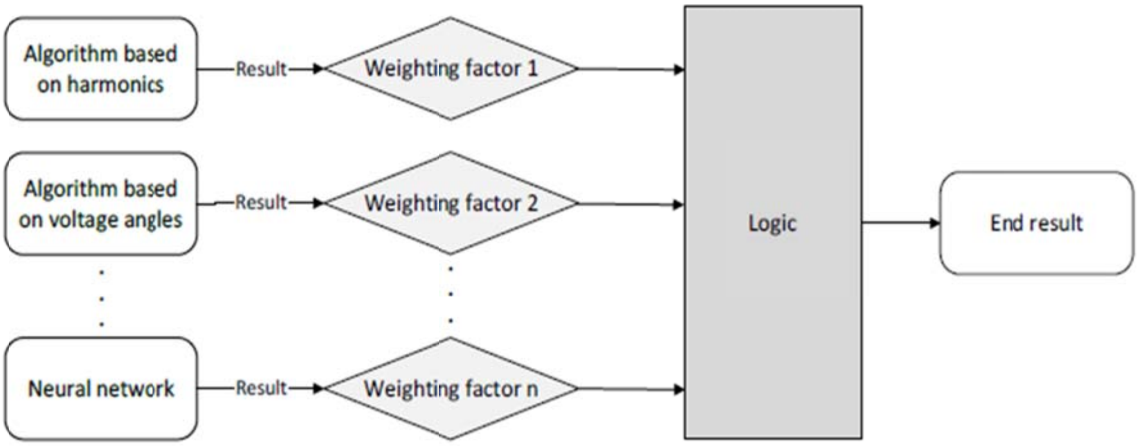

Figure14e: Structure of the secondary arc detection function

Source: Hu et al, 2023

Figure14e shows the addition of Neural Network as one criterion to detect the secondary arc.

2.3.6 Training of the Neural Network: As discussed in the research work by Hu et al., (2023), the addition of the Neural Network was as a criterion to detect a secondary arc based on the waveform of the open-phase voltage. A neural network results in an optimal algorithm for classifying between "secondary arc" and "no secondary arc" when trained correctly with a representative set of data. The Neural network shown in figure14f contains 9 neurons in three layers, during learning; the neurons optimized their weight factors. For a good result to be achieved a lot of training data is required. The training data consists of fault records done with an analogue channel representing the open-phase voltage and a binary signal representing the information about the presence of the secondary arc. According to the authors, most of the training data was computed by network simulation programs, simulating the different conditions of secondary arc. These training data was augmented by a large amount of fault records from "real" secondary arcs received from different customers around the world.

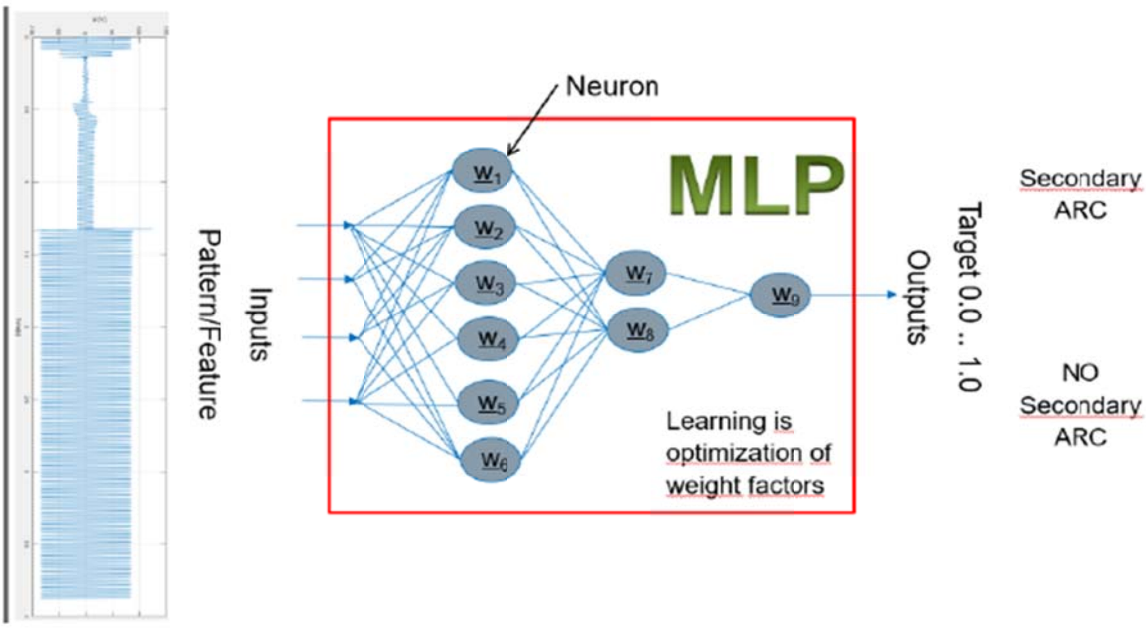

Figure14f: Learning process of the neural network used for secondary arc detection

Source: Hu et al., 2023

2.3.7 Major findings

According to Hu et al., 2023, the following three figures illustrate the successful function of the secondary arc detection of the implemented neural network. The figures are based on fault records showing the voltage of the opened-phase in **blue,** and the output signal of the neural network in **Red** colour.

Figure 14g shows a secondary arc which was extinguished in approximately 300 ms after the single phase tripping. The neural network detects the state change very fast and precise.

Figure14h is showing a secondary arc which is changing in its shape but does not extinguish during the single-phase dead time. The output of the neural network stable and indicate the presence of the secondary arc during the whole time.

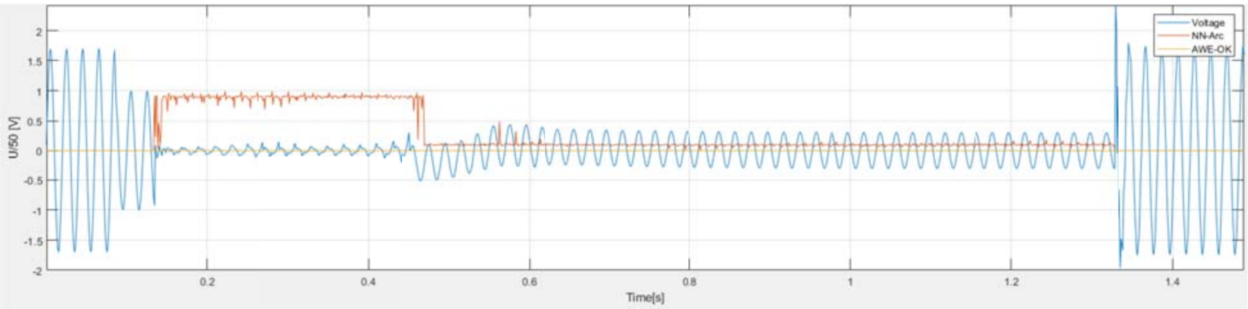

Figure14g: Detection of secondary arc extinguishing after single phase tripping

Source: Hu et al., 2023

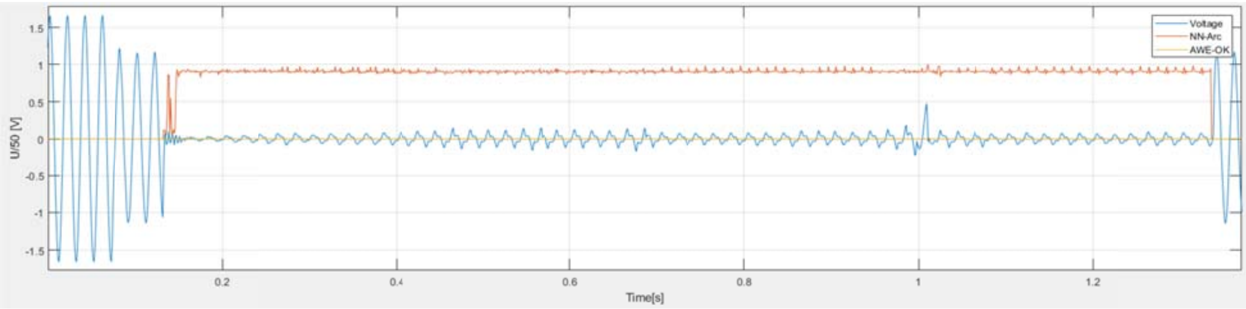

Figure14h: Secondary arc not extinguished during the dead time of autoreclosure

Source: Hu et al., 2023

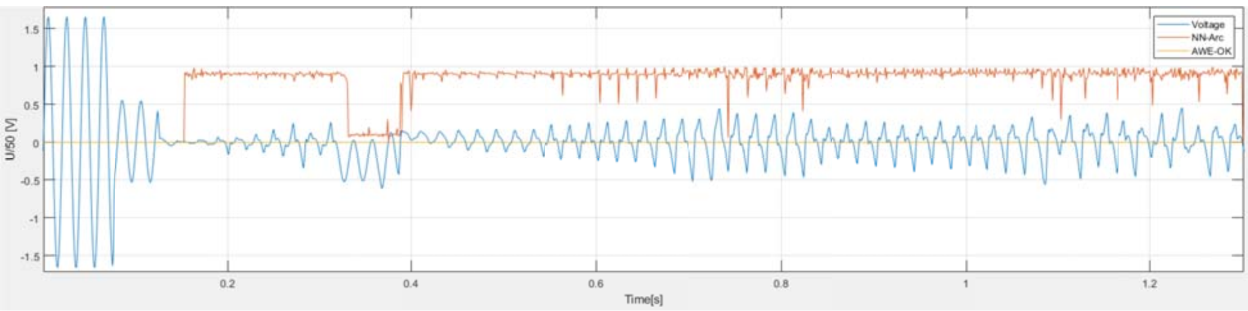

Figure14i: Detection of re-arcing after extinguishing of secondary arc

Source: Hu et al., 2023

Also figure14i shows a secondary arc which is re-arcing after extinguishing the first time. The neural network detects the first extinguishing of the secondary arc and the re-arcing very fast and precise. After the re-arcing, the output of the neural network was found to be correct but not as stable as in the previous results.

According to the authors, they concluded that due to the concept of using several criteria to detect the presence of the secondary arc, the risk of a malfunctioning in case of a secondary arc which was not detected with the neural network is minimized.

According to the authors, the AI/ML technology based application still have a long way to go before achieving deployment maturity, and wide-spread acceptance by utility and practicing engineers. The authors also asserted that the report will need updating within a space of 3 to 4 years. However, it is believed that AI and ML technologies are already helping engineers to optimized power system operations and protection.

3. CONCLUSION

The literature review indicated effort put into place to ensure power system reliability using machine learning techniques, and the success have made it promising to achieve optimal operation of the protection system to reduce incidence of system collapse and increase availability of the transmission network.

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