Indonesian Journal of Electrical Engineering and Computer Science
Vol. 43, No. 3, September 2026, pp. 709~717
ISSN: 2502-4752, DOI: 10.11591/ijeecs.v43.i3.pp709-717

Artificial neural network-enhanced solid-state DC breaker for ultra-fast protection in LVDC microgrids

Eswaraiah Giddalur, Askani Jaya Laxmi
Department of Electrical and Electronics Engineering, JNTUH University College of Engineering, Science and Technology Hyderabad, Hyderabad, India

Article Info

Article history:

Received Dec 24, 2024
Revised Jul 13, 2026
Accepted Aug 19, 2026

Keywords:

Artificial neural networks
Fault detection
Levenberg-marquardt
LVDC microgrids
Resilient power systems
Solid-state circuit breaker
Ultra-fast protection

ABSTRACT

Low voltage direct current (LVDC) microgrids are increasingly adopted due to their efficiency in integrating distributed energy resources (DERs) and DC loads without multiple conversion stages. However, the presence of high-amplitude fault currents and the vulnerability of electronic devices pose significant challenges to reliable protection. Conventional electromechanical switches suffer from slow response times, making them unsuitable for modern LVDC systems. Solid-state circuit breakers (SSCBs), with their millisecond-level interruption capability, offer a promising alternative. This paper introduces an artificial neural network (ANN)-based protection strategy integrated with a bi-directional SSCB for DC bus fault mitigation. The ANN is designed to optimize fault detection and clearing time, achieving rapid isolation within 0.25 ms. A feedforward two-layer neural network with 20 hidden neurons and a sigmoid activation function is trained using multiple algorithms, including Levenberg-Marquardt, Bayesian Regularization, and Scaled Conjugate Gradient. Simulation results demonstrate superior performance compared to conventional differential protection, with the LM algorithm providing the most accurate and efficient fault clearing. The proposed ANN-SSCB approach enhances system reliability, equipment safety, and overall resilience of LVDC microgrids.

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Corresponding Author:

Eswaraiah Giddalur
Department of Electrical and Electronics Engineering, JNTUH University College of Engineering Science and Technology Hyderabad
Hyderabad, India
Email: eshwar219@gmail.com

1. INTRODUCTION

The accelerating reliance on advanced technologies has intensified global energy demand, compelling modern power systems to evolve in efficiency, reliability, and sustainability. Emerging electricity grids must simultaneously address societal needs, environmental concerns, and economic constraints, while ensuring system security, power quality, and cost-effective transmission. The depletion of fossil fuels and the rise of greenhouse gas emissions have further driven the integration of renewable energy sources (RESs) into distribution networks [1]-[5].

Consequently, distribution grids are transitioning into active networks, incorporating distributed generation, RESs, and energy storage systems. In critical scenarios such as natural disasters or large-scale outages, microgrids (MGs) can operate autonomously, enhancing resilience and energy security. Among these, DC microgrids offer distinct advantages: direct integration of DC sources and loads, elimination of reactive power compensation, absence of synchronization requirements, and simplified integration of large-scale photovoltaic systems [6]-[10].

Despite these benefits, DC microgrids face significant challenges in fault protection, primarily due to the high magnitude of DC fault currents and the limited maturity of DC protection devices. Conventional electromechanical circuit breakers are inadequate, as their slow response times compromise equipment safety and system reliability. In contrast, solid-state circuit breakers (SSCBs) provide interruption within a few milliseconds, making them highly suitable for LVDC applications.

The LVDC microgrid considered in this study (Figure 1) comprises three distributors and nine loads-motors, heaters, and lighting-arranged in parallel groups through controllable switches [11]-[15]. With rated parameters of 48 V and 250 W per load, ensuring personnel safety, equipment protection, and regulatory compliance necessitates a robust DC bus protection system capable of rapid fault isolation. This paper addresses these challenges by proposing an artificial neural network (ANN)-based SSCB protection strategy, designed to achieve ultra-fast fault clearing and enhance the resilience of LVDC microgrids.

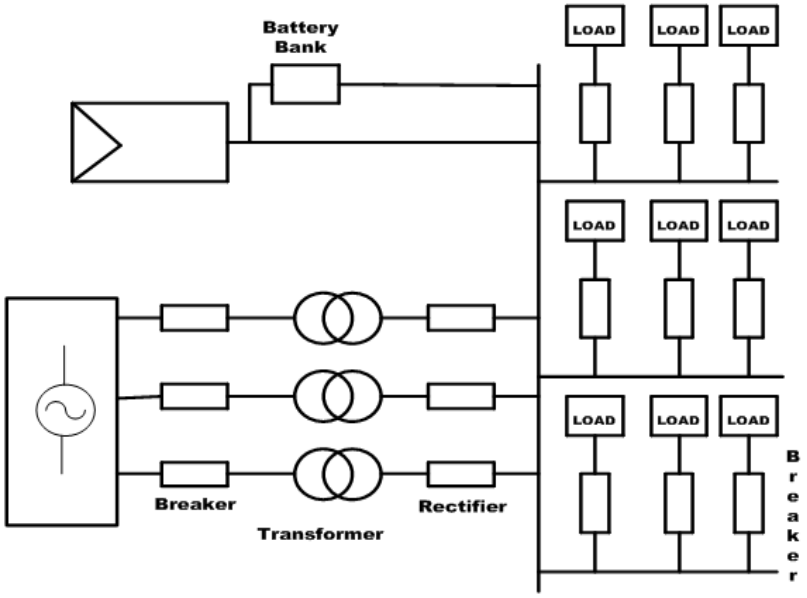


Figure 1. Block diagram of a LVDC microgrid

2. OPERATION OF SOLID-STATE CIRCUIT BREAKER BASED BI-DIRECTIONAL BLOCKER

SCCBs are much faster and more impulsive than electromechanical due to absence of any mechanical parts and are based of IGCTs which have lower ON state losses than IGBTs as shown in Figure 2, for protection against short-circuit failures, a bi-directional solid-state circuit breaker is linked in series with the DC bus [15]-[20]. It has two SCRs connected in reverse parallel, two insulated-gate bipolar transistors (IGBTs) connected in reverse series, a blocking capacitor (C), a TRIAC, and a heat release resistor.

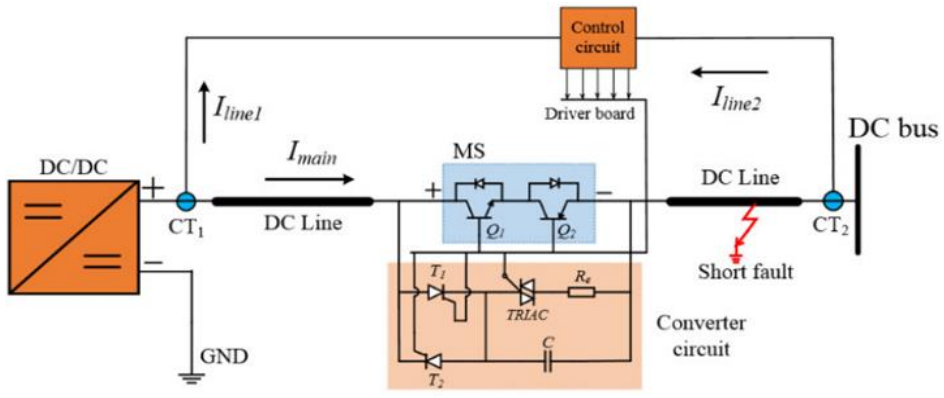


Figure 2. Block diagram of Bi-directional fault current blocker

SCR's and TRIAC components are in the OFF condition as shown in Figure 3. In Figure 3(a), under normal operation IGBT's are turned ON. The DC bus and BSCCB are linked in series, and the IGBT and reverse parallel diode receive the rated current. IGBT and diode conduction voltage drops are extremely minimal; hence the bi-directional blocker has low impedance and does not obstruct the normal operation of other components [21]-[24]. When fault occurs IGBT's are turned OFF while simultaneously turning on thyristor T 1 shown in Figure 3(b). The fault currents flow through thyristor and charging capacitor to external circuit. Gradually the fault current falls to zero. By absorbing the fault current, blocking capacitor is fully charged which makes the current through thyristor less than it's holding current value, and eventually thyristor is turned OFF, as shown in Figure 3(c). Figure 3(d) In final stage, the circuit breaker returns to its normal operating mode, turns ON the IGBTs, and the blocking capacitor discharges in the form of heat through the resistor (Re). However, these two operations do not collide with each other.

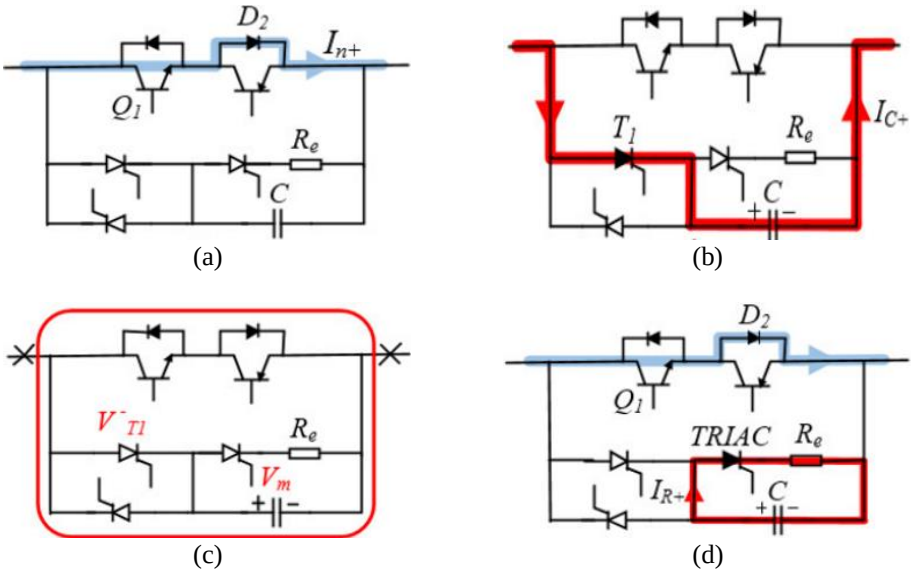


Figure 3. Operation modes of Bi-directional fault current blocker: (a) Mode-1, (b) Mode-2, (c) Mode-3 and (d) Mode-4

3. ANN PROTECTION STRATEGY

A Feed forward 2-layer neural network is created. The hidden layer has 20 neurons. Hyperbolic tangent activation function used to convert the activation level of a neuron to an output value in hidden layer in Figure 4 [14]. The hyperbolic tangent activation function is expressed as (1):

$$y = ftanh(x) = (e\text{^}(-2x) - 1)/(e\text{^}(-2x) + 1) \quad (1)$$

The output of the hidden layer can be simplified as (2):

$$g(I,V) = ftanh(W(1)(I,V)T \quad (2)$$

For the output layer activation function used is linear transfer function as shown in Figure 5.

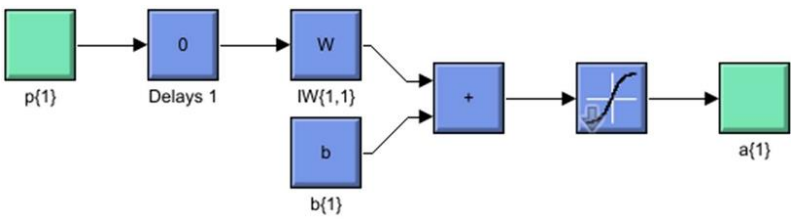


Figure 4. Hidden layer architecture

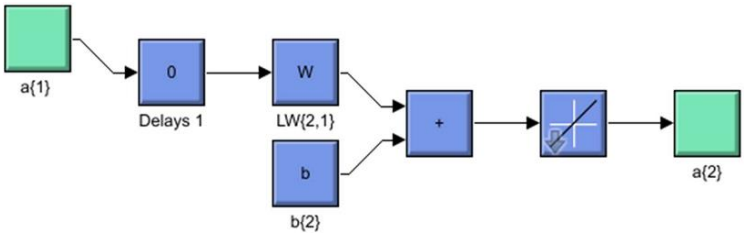


Figure 5. Output layer architecture

Table 1 shows the ANN architecture parameters. Figure 6 shows the training algorithm of ANN. ANN implementation has two possible ways: one is programming and the second is GUI tool. ANN training requires input data and target data, but using GUI tool, we can train the model. Each step may involve multiple sub-steps and iterations, especially in the training loop where forward and backward propagation are repeated for each epoch. The flowchart provides a clear, structured approach to developing and deploying an ANN.

Table 1. Feedforward ANN parameters

Parameters	specifications
Input layer neurons	2
Hidden layer neurons	20
Output layer neurons	1
Activation function	Tansigmoid
Number of training algorithm	3

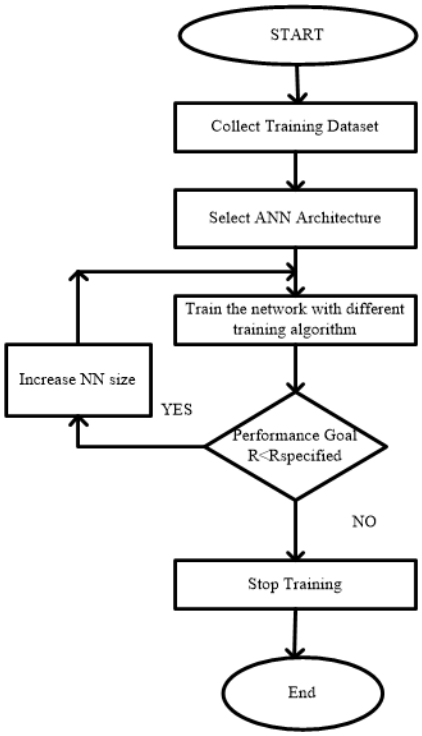


Figure 6. Training algorithm flowchart

4. SIMULATION RESULTS

The proposed model is shown in Figure 1. The Figure shows the supply voltage and three parallel transformers. Three transforms input connected to MV circuit breaker. The three-phase rectifier and DC bus protection circuit. Three-phase source protection system three DC parallel loads. The proposed simulation model parameters are:

- Energy release resistance Re = 100 ohms.
- Capacitance C = 0.4 mF.
- Equivalent inductance of the line L = 5 mH.
- Equivalent resistance of the line R = 0.1ohms.

For the majority of issues, Levenberg-Marquardt (LM) training is advised. Using the LM algorithm, a regression of 0.934 is obtained for training, shown in Figure 7, which indicates the input and output have a close relationship. It has high accuracy. Bayesian regularisation (BR) can produce a better solution for noisy or small datasets, but it takes longer. Using the BR algorithm, a regression of 0.89054 is obtained in training as shown in Figure 8, and the best performance is gained after 460 epochs. Figure 9 shows the scaled conjugate gradient (SCG), which employs gradient computations that consume less memory than the Jacobian calculations used by the other two techniques, is advised for use on big tasks. Using the SCG algorithm a regression of 0.82649 is obtained.

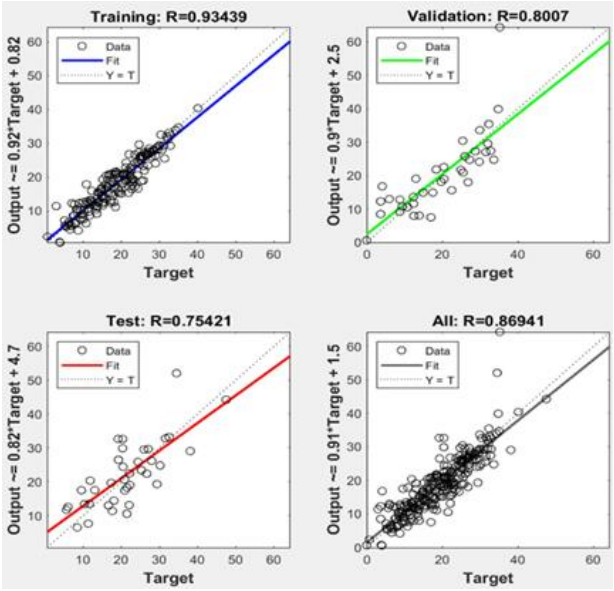


Figure 7. Regression for training, testing and validation using LM

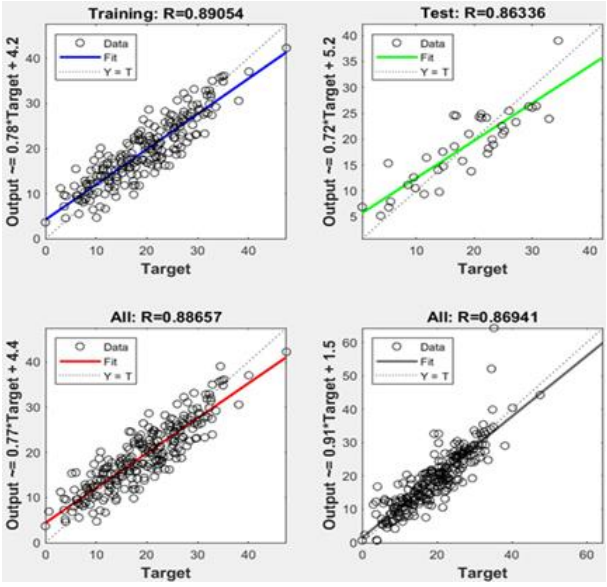


Figure 8. Regression for training, testing and validation using Bayesian regularization

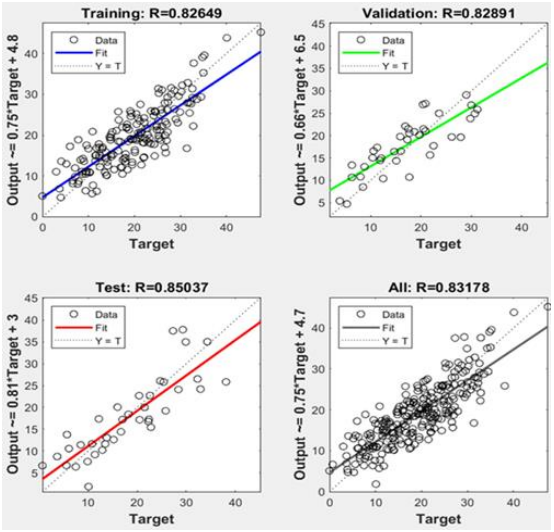


Figure 9. Regression for training, testing and validation using scaled conjugated gradient

The waveforms shown in Figure 10 depict the line currents at both ends of DC Bus. IF is the current at faulty end of DC Bus and IR is the line current flowing through the DC loads. ID is the fault transient obtained as difference of IF and IR. ANN protection clears the fault in 0.25ms. Figure 11 shows the fault transient response, indicating a rapid change followed by a stable condition. Figure 12 shows the voltage, current, and power waveforms of the DC load during and after the fault. Since, the fault is given in the interval 0.2s to 0.3s, the loads are isolated from fault current.

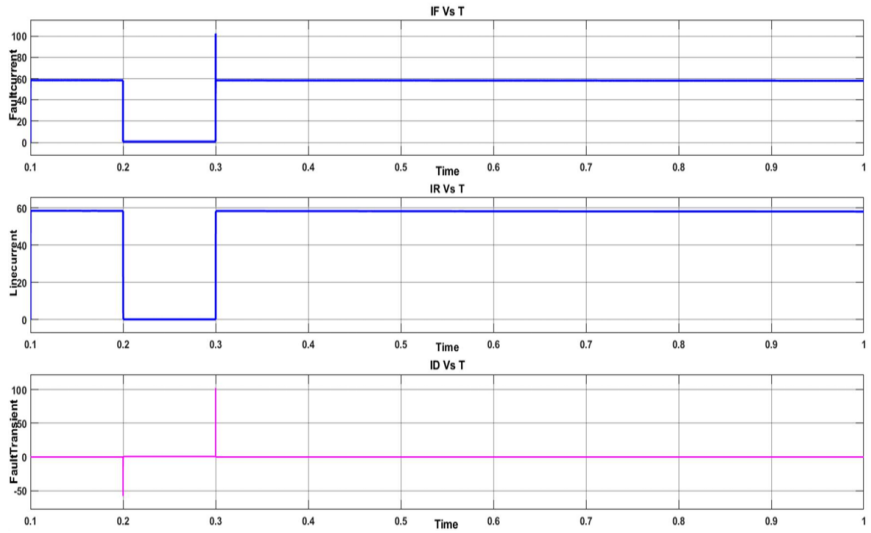


Figure 10. Waveforms of line current parameters of DC bus

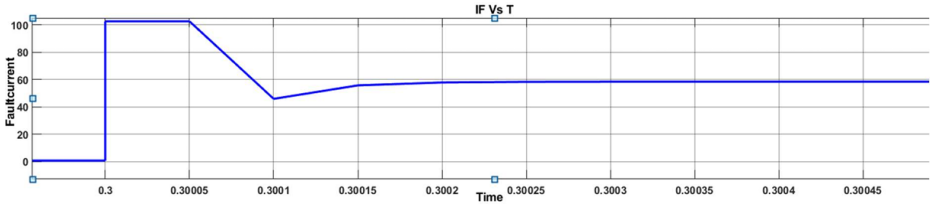


Figure 11. Waveform of fault transient

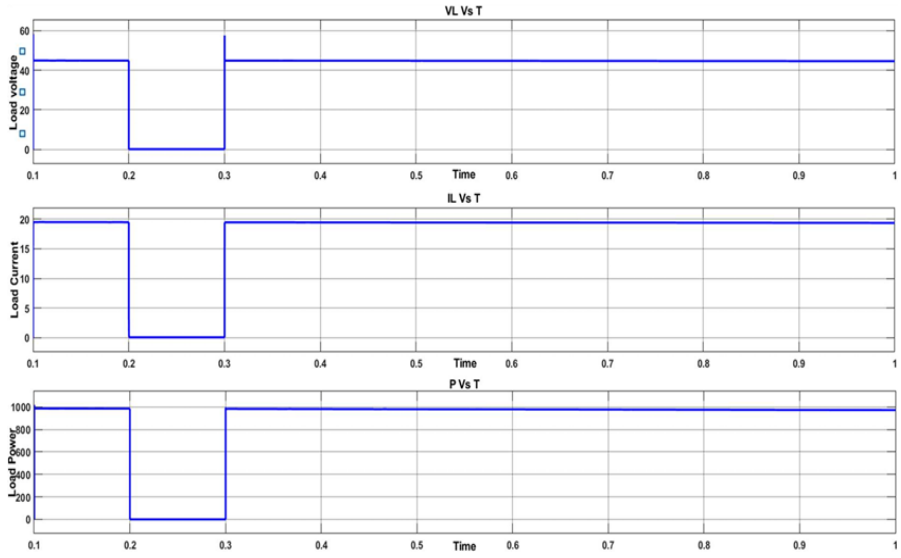


Figure 12. Waveforms of load parameters

Table 2 compares the fault clearing times of differential protection and the ANN training algorithms, showing the faster fault isolation achieved by the proposed ANN-based protection strategy. Figure 13 shows the three-phase rectifier circuit. This converter it converts three-phase AC supply to DC source. Three parallel 48V dc supplies are connected to rectifier output. Figure 14 shows the three DC loads are connected via feeder monitoring unit (FMU). The three DC loads are connected with DC Micro grid, the DC micro grid connected with three inputs solar, wind and rectifier circuit. The proposed algorithm will be implemented using the DSP 33EP512MU814. This CPU was chosen due to its advanced characteristics, which include high-speed pulse width modulation (PWM) with USB connectivity and advanced analogue technology. This CPU has the following features: It has an efficient code framework that supports both C and assembly languages. It supports seven PWM pairs, each with its own time and fault inputs that may be configured. Its powerful analogue technology supports two analog to digital converters (ADC), each with 32 analogue channels. This CPU also includes four 15 mbps universal asynchronous receiver and transmitter (UART) modules for flexible communication. The operational ranges are 3.0 V to 3.6 V, and -40 °C to +125 °C. Figure 15 shows the processor's on-board design. Figure 16 shows the battery bank, this battery bank connected between solar module and DC micro grid bus bar.

Table 2. Shows the fault clearing times of differential protection and the ANN training algorithms

Protection strategy	Fault time	Fault clearing time
Differential	0.1s	0.4 ms
Levenberg-Marquardt	0.1s	0.25 ms
Bayesian Regularisation	0.1s	0.27 ms
Scaled Conjugate Gradient	0.1s	0.27 ms



Figure 13. Three-phase rectifier circuit in ON mode



Figure 14. DC distribution system



Figure 15. DSP controller



Figure 16. Battery bank

5. CONCLUSION

This study demonstrates that conventional differential protection strategies are limited by higher fault transients and longer fault clearing times, making them less suitable for modern LVDC microgrids. Although both approaches detect faults at 0.1 s, the proposed ANN-based protection strategy achieves fault isolation in 0.25 ms, significantly outperforming the differential method, which requires approximately 4 ms. Among the evaluated training algorithms, the LM method proved to be the most effective, delivering superior validation performance within only five iterations. In comparison, Bayesian Regularization and Scaled Conjugate Gradient required longer training cycles and yielded slightly lower accuracy. The integration of ANN with a SSCB not only enhances fault detection speed but also improves overall system reliability, equipment safety, and resilience of LVDC microgrids. These findings highlight the potential of intelligent protection schemes to address the challenges of DC fault currents and establish ANN-based SSCBs as a promising solution for next-generation microgrid protection.

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BIOGRAPHIES OF AUTHORS



Eswaraiah Giddalur is received the B-Tech from JNTU Hyderabad, Hyderabad, India, in 2011 and received M-tech from JNTU Hyderabad, Hyderabad, India, in 2013. He is presently pursuing a Ph.D. in JNTUH University College of Engineering, Science & Technology, Hyderabad, India. He has presented technical papers in various National and international conferences. He has published papers in international journals. His area of interest includes Power Electronics, Power quality, microgrid, DC grid, DC bus protection. He can be contacted at email: eshwar219@gmail.com.



Dr. Askani Jaya Laxmi (Senior Member, IEEE) was born in Mahaboob Nagar, Andhra Pradesh, in November 1969. She received the B.Tech. Degree (EEE) from the Osmania University College of Engineering, Hyderabad, in 1991, the M.Tech. degree (power systems) from REC Warangal, Andhra Pradesh, in 1996, and the Ph.D. degree (power quality) from the Jawaharlal Nehru Technological University College of Engineering, Hyderabad, in 2007. She has five years of industrial experience and 20 years of teaching experience. She has worked as a Visiting Faculty at the Osmania University College of Engineering and is currently working as a Professor and a Local Coordinator, GIAN, JNTUHCEH, Kukatpally, Hyderabad. She has 110 international and national journals to her credit. She has 120 international and national papers published in various conferences held at India and also abroad. Her research interests are power systems, power quality, smart grid, and distributed generation. She is a member of various societies, like FIE, MIAO, MSSI, MISTE, MIETE, and MISC. She can be contacted at email: ajl1994@jntuh.ac.in.