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Integration of Flexible Interconnection Device in the Reconstruction of Medium and Low Voltage Distribution Networks Using DRL

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ABSTRACT: This article evaluates the connectivity with energy sharing in low-voltage distribution areas. Indicators like wind-solar complementing effectiveness, source-load energy sharing possibility, or transformer capacity interconnection measurements are part of the assessment index framework for interconnection capacity that is established after an analysis of the features of linked scenarios. Radial and inflexible, conventional distribution systems can't handle bidirectional power flow, fluctuating demand, or grid disruptions. Using real-world examples, we can see that the suggested strategy improves power supply efficiency across zones and increases the usage of distributed energy resources, proving the method's validity. With the help of Flexible Interconnection Devices (FIDs), MV/LV networks may be reconfigured, power quality is improved, DERs are supported, and reliability is increased. With so many distributed PVs connected to distribution substations, managing low- and medium-voltage distribution networks is a real challenge. One novel kind of power gadget that permits adaptable connections between distribution substation segments is the soft open point (SOP). This article presents learning algorithm for low and medium voltage networks for power optimization, which takes into consideration the dynamic connectivity of different areas of substation. The next stage is to construct a multi-agent deep reinforcement learning (DRL) suitable for low and medium voltage distribution networks using Deep Q Network (DQN) model in DRL. The low and medium voltage distribution network employs flexible interconnection device for power loss reduction. Finally, the case studies show that the proposed approach has a good operating strategy for distribution networks with medium and low voltages, and it may lessen voltage fluctuations caused by high PV integration.

KEYWORDS: Distribution substation area; flexible interconnection device; cooperative operation optimization; distributed photovoltaic (PV); DQN; DRL

1 Introduction

The system of interconnected electrical components that provides consumers with electricity is called an electrical power system. It has a plethora of buildings and infrastructure, tools and parts, systems and subsystems, and intricate relationships between them all [1]. Generation, transmission, and distribution are the three main parts of an electrical power system. The consistency of the power source is an aspect of power quality. The dependability of power systems is expected to be the greatest, and they are among the most complicated large-scale engineering systems in use today [2]. For distribution services, system reliability has always been a major challenge [3]. The distribution system is a major cause of the increased frequency of customer reliability problems. Consumers' power consumption is affected by the distribution network's mode of operation or any changes in its condition. Because of its proximity to end users, the distribution



system is an essential part of the electrical grid [4]. The rapid expansion of renewable energy sources and worldwide legislative incentives for decentralized power generation have led to the replacement of large-scale power stations with low and medium voltage distribution regions as the primary means of connecting dispersed power generation to the grid [5]. However, problems like a source-load mismatch in terms of time and geography might emerge when large-scale distributed power grids can't handle the demands that certain low and medium voltage distribution stations have—a lot of unpredictable loads.

A great deal of research in the past few decades has concentrated on the local power consumption under load randomized conditions in medium and low voltage transmission zones [6]. Despite their usefulness in storing energy from electricity for later use, batteries for energy storage aren't a panacea for source-charge inconsistency due to factors like investment expenses and the capacity for storage of individual low-voltage power transmission stations. One possible solution to the source-charge mismatch is to use low-frequency load shedding [7]. Using this approach weakens the electrical distribution network's reliability and reduces the load supply of electricity in part. Studies have demonstrated the advantages in both typical and non-standard operating conditions, including reactive power reimbursement, control of flow, regulation of voltage in systems, and rapid isolation of faults and supply restoration under non-standard settings [8]. Here is a method to find out whether a FID can take the place of traditional voltage control methods. Also, the monetary gains from expanding the distribution of viable DG were investigated in a case study. The study suggests an organized management technique for an AC/DC mixed distributive system with FID, nevertheless they don't mention what kind of function is failing [9].

Various studies have examined the potential of demand-side management flexibility, load-shedding, and generation redispatching for controlling power flows. This study presents a novel Deep Reinforcement Learning (DRL)-based approach to ensuring FID with medium and low power and voltage adjustments, while also addressing a number of existing restrictions. The proposed agent is data-driven that acquires the ability to regulate power flow from zero [10]. Grid operators may benefit from its ability to automatically adapt its topology to system conditions, allowing for more effective preventive control activities. A dueling double deep Q-network employing prioritized replay, the most current RL approach, is used to train an effective agent that can attain the goal performance. With just nine operations to modify the substation configuration utilizing the IEEE 33-bus protocol, the proposed agent is shown to run the power system for up to one month, demonstrating its usefulness and promising performance.

2 Background

Carrying and delivering electricity is a critical function of distribution networks in the energy and power network. For the advancement of decarbonization and the creation of new power systems, this function is of paramount importance. The increasing number of DGs connected to distribution networks and the challenges of load diversification in modern big cities have led to complicated operating modes and uneven power flow dispatch. Because of this, people start to question the stability of the events and the dependability of the power source. Uneven power capacity, lack of room for DGs, high power flow congestion, rapid localized rise in load demand, and limited system flexibility are particularly critical challenges that need immediate attention [11–13].

The quick localized increases in demand have led to substation transformer overloading, feeder load disparities, and inadequate protection against outage threats in constrained distribution corridors. The distribution network's reliance on contact switches and the original idea of “closed-loop architecture, open-loop operation” led to inadequate regulation. In addition to DGs' already limited carrying capacity, these issues further constrain their overall capacity and utilization by causing overvoltage's, unpredictable currents, along with power losses to substations. The rapid growth of EVs and charging stations, along with

distributed and centralized energy storage systems, additional PED loads, and congestion management in the distribution network, has made the problem of bidirectional power flow even more problematic.

The patterns of “power source with power load” interactions are being impacted by the integration of renewables and PED-driven power needs, which are causing significant changes to power supply with network compositions. Meanwhile, advancements in PED also open the door to better distribution network operations. The FID-based distribution network has many benefits over the traditional radial distribution network, including the ability to achieve asynchronous “closed-loop” operation, power flow transfer, load-rate equalization, continuous power supply, and rapid system restoration. In Table 1, we can see how FID technology has improved distribution networks by comparing and contrasting the key features of conventional networks with those of FID-based systems [14,15].

Table 1: Traditional distribution networks and their FID-based

Factors	Frequent distribution system	Distribution network based on FID
System structure	Radial structure	Interconnected structure
Investment	Low	High
Controlling the flow of power	Unidirectional power flow	Controllable power flow
Reliability of the power supply	Low	High
The ability to adapt operations	Low	High
Minimizing intricacy	Low	High
The capacity to extend the system	Low	High
DG network	Low	High

3 Related Work

The authors in [16] presented a control technique that utilizes a static synchronous compensator in conjunction with a four-leg three-phase four-wire parallel active power filter. The rapid development of power electronics and distributed energy resources has led to the widespread use of high-power equipment with nonlinear loads. The distribution network now needs to deal with voltage variation, harmonics, and three-phase imbalance, among other power quality issues, despite the fact that productivity has increased substantially. That work [16] presented a control technique that utilizes a static synchronous compensator in conjunction with a four-leg three-phase four-wire parallel active power filter. With the improved design technique for critical parameters and the suggested strategy, power quality concerns caused by unfavorable grid voltage with asymmetric loads might be efficiently addressed. Results from MATLAB/Simulink simulations confirm that the suggested strategy is successful; it has the potential to increase power quality while also ensuring voltage stability in medium and small voltage distribution networks.

In order to identify and localize faults, the researchers in [17] suggest using fiber optic sensor technology, which has several advantages, including great sensitivity, robust anti-interference capabilities, and real-time monitoring of physical characteristics like strain, temperature, and vibration. In order to identify critical defect characteristics in the data acquired by a fiber optic sensor-based monitoring system, signal processing methods like wavelet along with Fourier transforms are used. Additionally, for accurate localization and fault classification, machine learning models like Gradient Boosting Machine while Support Vector Machine are used. The experimental findings show that the suggested technique is more efficient and dependable than standard methods in identifying and localizing defects under different operating situations. In addition to advancing the state-of-the-art in fault detection and decision-making systems, that method provides a viable option for the intelligent management and upkeep of distribution networks.

The complexity of planning and building power grid networks, along with the ever-increasing demand for electricity across China's entire population, has made optimizing the design of low voltage distribution networks and boosting investment efficiency and distribution network planning a top priority for power grid businesses, according to [18]. In that paper, they take a look at the state of medium low and medium voltage distribution network building in one area of GD province, identify the current issues, and then use the relevant principles of an improved genetic algorithm to optimize the investment while construction of these networks. They then test the model to make sure it works.

The authors of [19] proposed a grading system based on their professional judgment. Project economic benefits, construction urgency, implementation effect, and power supply dependability are the four aspects that are considered to design a system for complete scoring indices for task optimization. As a second step, we employ a hierarchical analytic strategy to discover the overall weight, a Delphi method to find the experts' opinions' concentrations and dispersions, and a consistency method to get their study results. Finally, by giving the index system weights, they may be able to receive the whole preferred rating results for the project. An example's findings demonstrate that the optimization scored approach is successful, reasonable, and scientific, and that it considers the time pressure of project building in addition to the advantages of investments.

A technique for calculating the integrated sensitivity to cross voltage levels in an unbalanced medium- & low-voltage distribution system is proposed by the authors of [20]. First, the transformer's equivalent model under Dyn11 wiring is examined. Second, they develop and objectively examine the correlation between the main along with secondary sides of the transformer's voltage, current, and power. Lastly, the technique for calculating the integrated sensitivity of the MV-LV distribution system is constructed from the observed correlation relations. The MV-LV distribution network's inter-voltage and inter-phase sensitivity may be computed using that approach. In order to explore how power quality as well as inter-phase power propagate in an MV-LV distribution network, the Dyn11 transformer is used for the case study.

The authors of [21] have done a lot of study on the subject of reactive power mitigation in low voltage distribution networks. The present electricity system has significant issues with poor dependability, substantial line loss values and calculation errors, and severe data missingness. When analyzing power system network losses, the hierarchical node recognition method is used. In order to acquire different load nodes rapidly, they researched the intelligent identification technique that uses SVM. Decrease the occurrence of network loss problems due to data that is not current. Optimal voltage while reactive power is achieved by meticulously coordinating each connection. The low-voltage distribution network region in question is modeled. The algorithm is shown to be workable by the findings.

The method of establishing the budget before to the project is used by researchers of the [22] distribution network development project. Therefore, a collection of useful models to assess investment viability and investment income rationale is urgently required. Considering aspects like security, maturity, economics, applicability, along with green environmental protection, that study offers solutions to improve voltage quality by using new technologies. In order to do this, it develops initiatives for building and planning the power system and investigates the reasons behind poor voltage quality. With the goal of enhancing the voltage quality of medium while lower voltage distribution networks, the optimization method to voltage quality improvement projects is investigated and built. The planning works in a certain region are ranked using the model, and the resulting rankings are in line with the planned planning goals. The model's accuracy and reasonableness are subsequently confirmed by a variety of real-world initiatives.

In their study, the authors of [23] looked at a new kind of source-charge access network that combined medium-low voltage AC/DC hybrid components with a centralization-distributed control approach. Two distribution systems are optimized: one for medium voltage, which maximizes economy, and another for low

voltage, which eliminates power fluctuation. While designing optimization control models for low voltage networks, it is important to consider their unique network topologies, control hardware, and control time scales in order to accomplish cooperative management of medium voltage AC-DC hybrid distribution systems. The proposed technology is effective in decreasing low-voltage voltage fluctuations and enhancing PV absorption capacity, as confirmed by a medium voltage 27-node medium voltage AC-DC hybrid power distribution network.

The primary purpose of [24] is to provide the context, relevance, and goals of the topic study. The system design details the steps used to set up the system and its ultimate functioning, whereas the demand analysis primarily provides an overview of the structure with its functional needs. That section provides a synopsis of the evolution of low and medium voltage technology as well as its current trend in distribution network applications. Tools and models to assess loads and power quality in electricity supply system branches and nodes are necessary due to the growth in electric energy consumption and the integration of renewable energy sources into low and medium voltage distribution networks. Authors of [25] provide a DN model that can mimic loads and sources varied operating regimes. Connected to one of the substations in the model, a battery energy storage system may be seen as a DER, or distributed energy resource, as it can either produce or consume energy. Therefore, the model may be used to investigate DN behavior in relation to reactive power levels and voltage quality, as well as to evaluate various control methods in the presence of digital substations with smart grid.

Contribution of the Study

- Flexible Interconnection Devices (FIDs) can be used to improve power quality, support DERs, increase dependability, and reconfigure MV/LV networks.
- Managing low- and medium-voltage distribution networks is extremely difficult due to the large number of dispersed PVs linked to distribution substations.
- The soft open point (SOP) is a new type of power device that allows flexible connections between distribution substation segments.
- This paper introduces a novel learning technique for power optimisation in low and medium voltage networks that takes into account the dynamic connection of various substation locations.
- The next step is to use the Deep Q Network (DQN) architecture in DRL to build a multi-agent DRL that is appropriate for low and medium voltage distribution networks.
- Flexible connector devices are used in the low and medium voltage distribution network to reduce power loss.
- Lastly, the case studies demonstrate that the suggested method may reduce voltage fluctuations brought on by high PV integration and has a good operating strategy for medium and low voltage distribution networks.

4 Materials and Methods

Flexible Interconnection Device with Low Voltage and Medium Voltage Networks

It is common practice to use the complete control device as the foundation for a flexible DC connectivity device. Among the many FID functional designs made possible by the power electronic device's versatile operation control mode are power transfer during normal operation and distribution network fault recovery. Fig. 1 shows the interconnection of FID with low voltage and medium voltage networks. With the FID's built-in bidirectional power converter, power may be transferred in either way from either terminal A or B. In order to stabilize the DC voltage and enable system operation in normal and partial fault circumstances, a central controller of both reactive and active power controls the two inverters. It is possible that certain regions have a larger load density and so more scattered power generating permeability, leading

to power surpluses in such regions. By transferring power to both stations via the FID link, the station's power shortfall may be reduced and the dispersed power output's capacity increased. The low-voltage section of the distribution network's power supply is made more reliable when, in the event of a problem in one terminal zone, an additional terminal can continue to service multiple critical loads in the affected area.

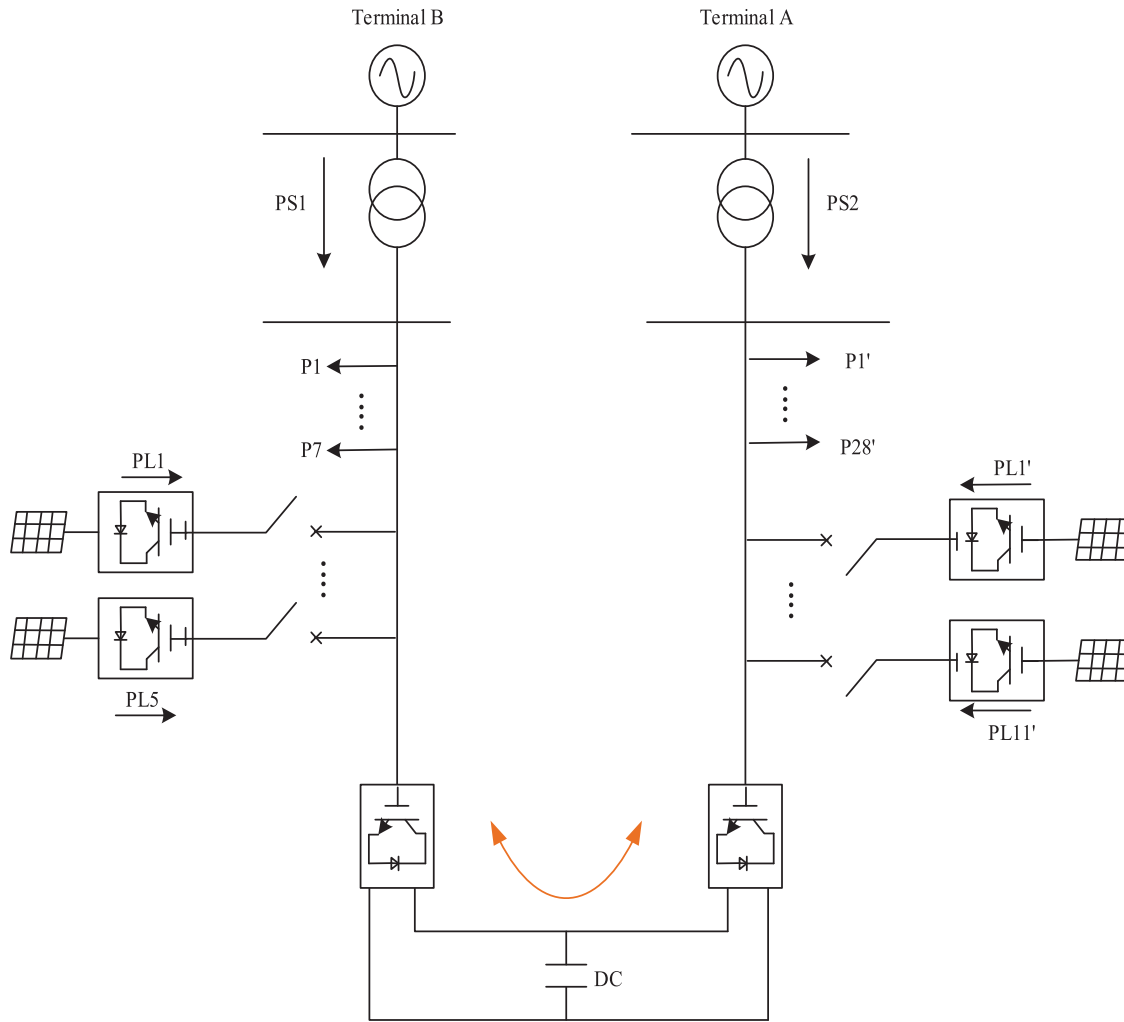


Figure 1: Adaptable network architecture for medium and low voltage distribution

Under typical operation, the FID's access allows for a bidirectional power supply at both A and B terminals; nevertheless, in the event of a problem, the FID may aid in restoring power to the malfunctioning terminal. Nevertheless, FID is limited in its ability to restore power to all places that have been de-energized due to a failure since it is a power electronic device. If a fault takes place at one terminal, the first step in recovering from a failure is to lock the FID and activate the line protection relay device associated with the problem. Once the problem has been resolved, the FID could supply power to the affected load segment from the healthy terminal.

The standard AC bus's voltage amplitude and frequency are kept constant by the constant voltage and frequency control, which responds to variations in the inverter's output. Both the PQ and VF controllers theoretically derive their architectures from the identical current inner loop control technique, with the exception that the VF controller uses different modes for the outer loop.

4.1 Working of Flexible Interconnection Device for LV and MV Distribution Networks

The benefits of the aforementioned design are listed below. First, without taking into account the particular composition of resources inside the distribution substation regions, the areas engage in medium-voltage optimization collectively. Solving centralized optimization issues becomes more easier and smaller as a result of this. Furthermore, in order to mitigate the effects of inaccurate day-ahead forecasts and enhance the capacity to control voltage fluctuations, in conjunction with voltage-reactive power adaptive adjustment, the low-voltage.

Distribution substation areas use a rolling solution strategy. Finally, with the help of medium-voltage side instructions, the autonomous and coordinated operation is achieved by means of distributed optimization in the interconnected and flexible distribution substation regions. Regarding the medium-voltage side as well as handling a large share of PV access, this also guarantees the safe and effective functioning of the distribution substation region. The control architecture is shown in Fig. 2 below.

Adaptable distribution substation sites connected in a flow diagram for low and medium voltage networks.

- (1) Mid- and low-voltage distribution network critical parameters.
- (2) Using the above parameters, find the distribution substation zone's power correlation constraint with flexibility region constraint.
- (3) Every day, the medium-voltage section of the distribution network coordinates addressing problems and issues instructions to the side of the distribution substation. The instructions include the voltage reference values $V_{t,T}^{\text{ref}}$, active power reference value $P_{t,T}^{\text{ref}}$, and reactive power reference value $Q_{t,T}^{\text{ref}}$ across all areas of distribution substations.
- (4) The adaptive regulation curve for voltage-reactive power is created by every zone of the distribution substation.
- (5) Within the adjustable interconnected distribution substation area, the voltage at the connection point is monitored at the current optimization period. The distribution substation region uses the voltage-reactive power adaptive regulatory curve that was established to calculate the desired value of reactive power output.
- (6) In order to minimize the entire operating expenses of the distribution substation area, it is necessary to create an optimization model that accounts for its linked flexibility.
- (7) In addition to daily distributed optimization execution, the distribution substation area also shares border information with neighboring areas.
- (8) The optimization results should be reported if the r -th iteration's boundary information error is less than or equal to the convergence accuracy ε . Return to Step 7 if you need to alter the boundary interaction settings.
- (9) Finalize the calculations and proceed if each day's optimization time has reached its limit. If not, go on to the next optimization phase and repeat steps 5 and 6.

4.2 DRL-DQN

The agent in this study makes decisions based on its interactions with its environment at discrete timesteps. The agent chooses an action a_t from set A, while the setting is represented through states s_t from set S. The agent receives a reward from the environment in response to the action they choose $r_t = r(s_t, a_t)$ the subsequent new state s_{t+1} is generated. Return after discounting is defined as $G_t = \sum_{k=0}^{\infty} \gamma^k R_{t+k+1}$ as the representative exploits it to its full potential. A constant γ , that may have values between 0 and 1, determines the relative value of delayed vs. instant reward.

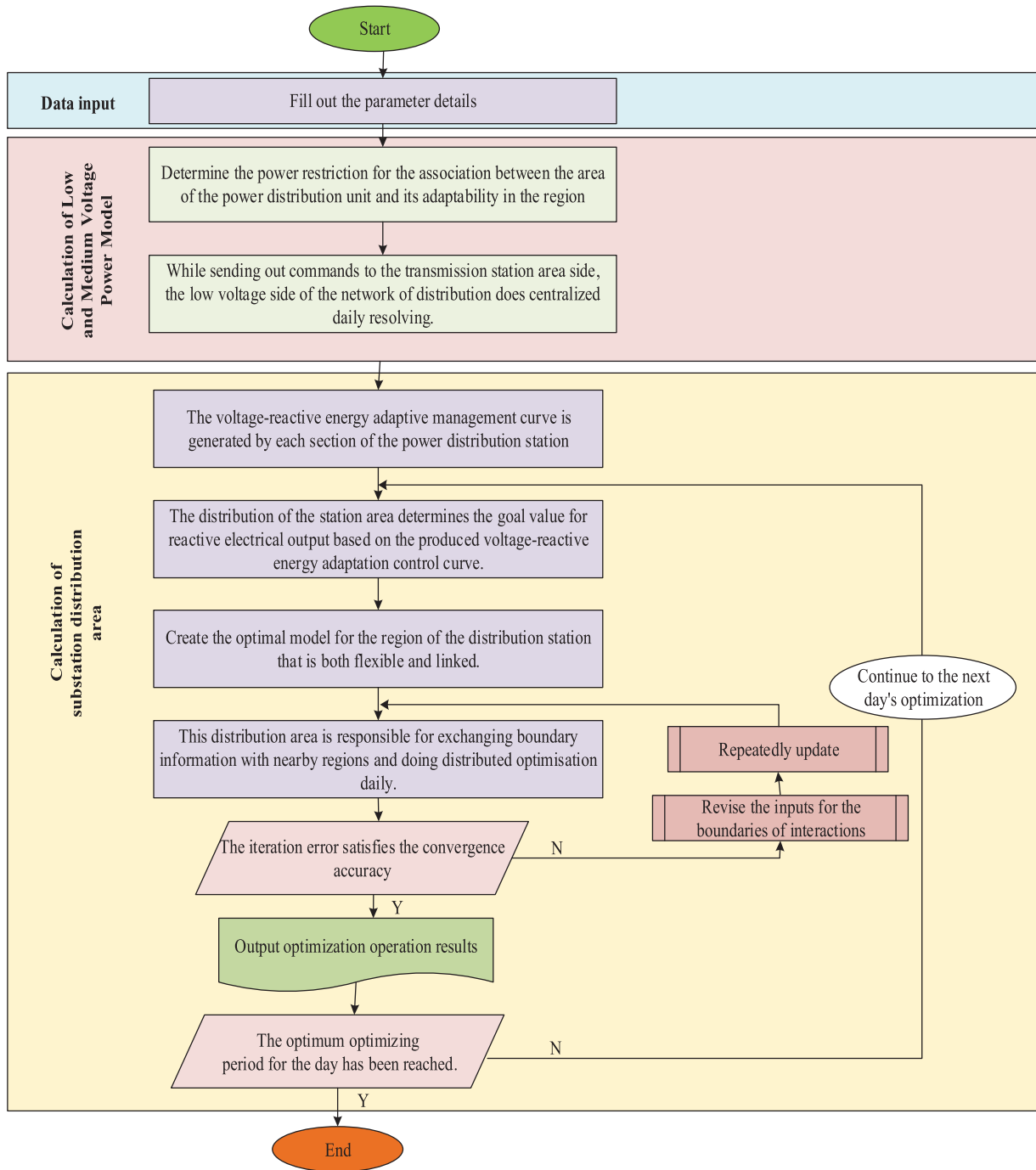


Figure 2: Power Optimization between Low and Medium Voltage Networks with FID

Value functions are used to measure the goodness of an agent's current condition in terms of potential rewards. In the case of an agent whose behavior is dictated by a random policy π , the value function $v_\pi(s)$ and of the action value function $q_\pi(s, a)$ are well-defined as follows:

$$\begin{aligned} v_\pi(s) &= \mathbb{E}_\pi [G_t | S_t = s] = \mathbb{E}_\pi [R_{t+1} + \gamma R_{t+2} + \gamma^2 R_{t+3} + \dots | S_t = s] \\ q_\pi(s, a) &= \mathbb{E}_\pi [G_t | S_t = s, A_t = a] = \mathbb{E}_\pi [R_{t+1} + \gamma R_{t+2} + \gamma^2 R_{t+3} + \dots | S_t = s, A_t = a] \end{aligned} \quad (1)$$

This is the best action-value function $q_*(s, a) = \max_{\pi} q_{\pi}(s, a)$, for all $s \in S, a \in A(s)$. It abides by a crucial identity called the Bellman equation:

$$q_*(s, a) = \mathbb{E}[R_{t+1} + \gamma \max_{a'} q_*(s', a')], \text{ for all } s \in S, a \in A(s) \quad (2)$$

Estimating the action-value function (Qfunction) through repeated updates to the Bellman equation is the fundamental principle behind several RL techniques. One method for controlling temporal differences that does not include policies is Q-learning:

$$Q(S_t, A_t) \leftarrow Q(S_t, A_t) + \alpha [R_{t+1} + \gamma \max_a Q(S_{t+1}, a) - Q(S_t, A_t)] \quad (3)$$

where the learning rate is denoted by α . The best action-value function may be found via value iteration algorithms regardless of the policy that is implemented. When trying to compute the action-value function, it is usual practice to employ a function approximator like a neural network $\tilde{q}(s, a, w) \approx q_{\pi}(s, a)$. The weights, w , of the approximator are used by a neural network algorithm to convert states to Q-values. Some modifications to the weight updates may be made in order to train a Q-network:

$$w_{t+1} = w_t + \alpha [R + \gamma \max_a \hat{q}(S_{t+1}, a, w_t) - \hat{q}(S_t, A_t, w_t)] \nabla \hat{q}(S_t, A_t, w_t) \quad (4)$$

where w_t , S_t and S_{t+1} are the neural network's preprocessed observation inputs at timesteps t & $t + 1$, respectively; A_t is the action chosen at time step t , and is the vector containing the network's weights. We used backpropagation to calculate the gradient in of the Q-network. As a foundational DRL algorithm, DQN is used to train an agent for electrical system controller. Nevertheless, this technique is recognized to have a number of drawbacks. Therefore, the baseline model used for this study is double dueling DQN and prioritized replay. The agent is responsible for controlling power system congestion and preventing failures and blackouts that might cause a domino effect. To achieve this goal, we focus only on behaviors related to grid topology reconfiguration.

5 Results and Analysis

The cooperative operation optimization strategy is shown to be beneficial for low and medium voltage distribution systems with flexibly connected distribution substation areas in this section. When applied to MATLAB R2020a, the proposed method makes use of the CPLEX 12.10 method included in YALMIP. An Intel Core i7 CPU running at 2.50 GHz with 16 GB of RAM was required for the numerical testing.

Fig. 3 depicts the architecture of the revised IEEE 33-node structure. Testing the Distribution Substation Areas' Flexibility and Adjustability and the medium-voltage distribution system defines the adjustable distribution substation zones by integrating the constraints of the correlation power of the substation area with the boundary conditions of the flexibility zone. The following comparison schemes are set up to validate the effects of considering correlation power restrictions and flexibility region constraints on the operation of low and medium voltage distribution systems:

- Scheme 1: We employ the centralized optimization of the medium-voltage distribution network, ignoring the areas of the substations that may be changed.
- Scheme 2: We consider the distribution substation regions' flexibility via centralized optimization on the medium-voltage distribution network.

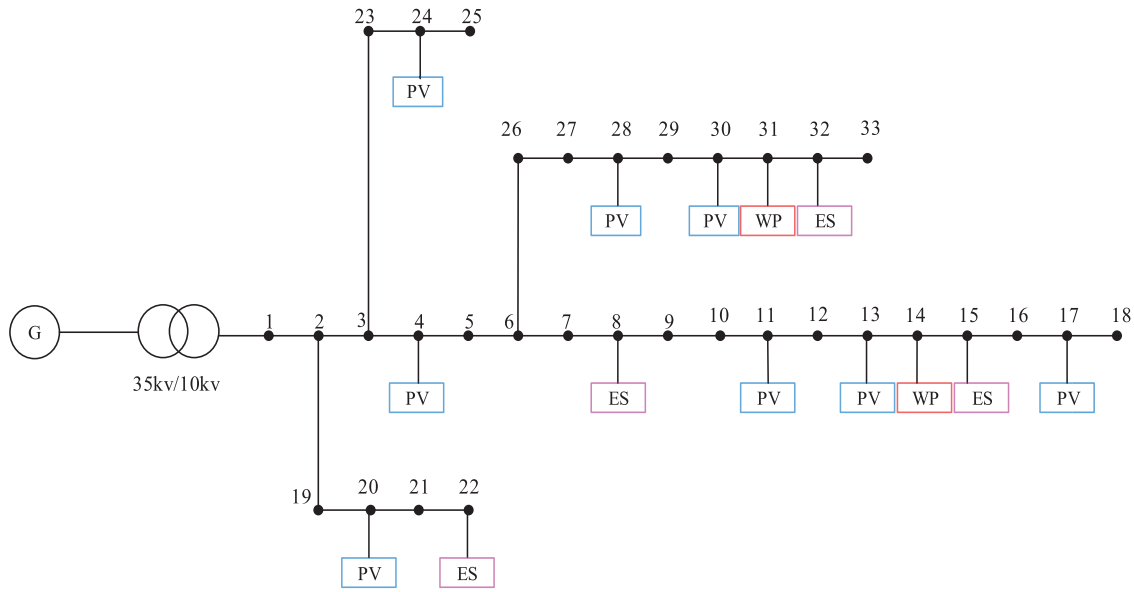


Figure 3: IEEE 33 node structure

Table 2 shows the system parameters. Topological operations that may be performed in the simulator include:

- Altering the substation setup
- Linking or disconnecting a line.

Table 2: System parameters

Variables	Value
Peak demand	9.0 + 2.6 MVA
Substation voltage	5.54 p.u (13.77 kV)
V_{min}	0.87 p.u
V_{max}	1.08 p.u
S_{maxPV}	1.9 MVA

It is possible to split a substation in half and modify one substation every timestep. We need to let a switched line or node 15 min to cool down before you may use it again.

An agent's perception of the power grid may be described by an observation. The viewing area, with all relevant information, is defined according to Table 3. At the current time step, the observations include 368 features. By reducing the observation area, we were able to record powerline capacity, currents and voltages on both branches, with a topology vector indicating which bus each item is connected to (load, generator, powerline endpoints) is attached in its substation. Table 3 holds the qualities that were chosen from the reduced observation space, which comprises 157 features. The neural network's input layer occupies 157 square pixels of area for observations. As the action space grows in size, so does the output layer, which corresponds to the number of possible actions. One hundred and twenty-eight neurons make up each of the two buried levels. At last, we used a simple reward function which merely keeps track of the agent's timestep performance. It incorporates a continuous incentive for every timestep that is well managed.

Table 3: Main observation attributes

Feature	Size	Category	Designation
Date	8	Int	Year, month, day, hour_of_day, minute_of_hour, day_of_week
Current powerline status	22	Bool	Line_status
Measurements taken in time due to an overflowing powerline	24	Int	Timestep_overflow
The substation is inaccessible for a certain number of timesteps.	13	Int	Time_before_cooldown_sub
Power in action	58	Float	Gen_p, load_p, p_or, p_ex
Reaction potential	58	Float	Gen_q, load_q, q_or, q_ex
Voltage	59	Float	Gen_v, load_v, v_or, v_ex
How many timesteps does the powerline not work?	25	Int	Time_before_cooldown_line
Current	43	Float	a_or, a_ex
Electrical line capacity	25	Float	Rho
Vector representing topology	55	Int	Topo_vect

Algorithm Selection and Hyperparameters Used

We focus on DQN and its variants because of the algorithm's simplicity, the discreteness of the chosen observation space with action space type, and other relevant factors. For this investigation, the deep Q Network technique and its variations were discovered in the RLlib standard library. All of the DQN improvements mentioned in are implemented by them. One of the most successful variants of DQN, the dueling double DQN employing prioritized replay algorithm, was employed in this investigation. Every hyperparameter used in this research for RL agent training was either left at their default settings in Ray RLlib's DQN algorithm or adjusted in accordance with the criteria laid forth in [Table 4](#).

Table 4: Research's hyper parameters

Hyperparameter	Value
learning_start	5000
train_batch_size	68
model_fcnet_hiddens	[125, 125]
target_network_update_freq	277
learning rate schedule	lr_start = 10×10^{-5} lr_end = 10×10^{-6} lr_time = 100,000

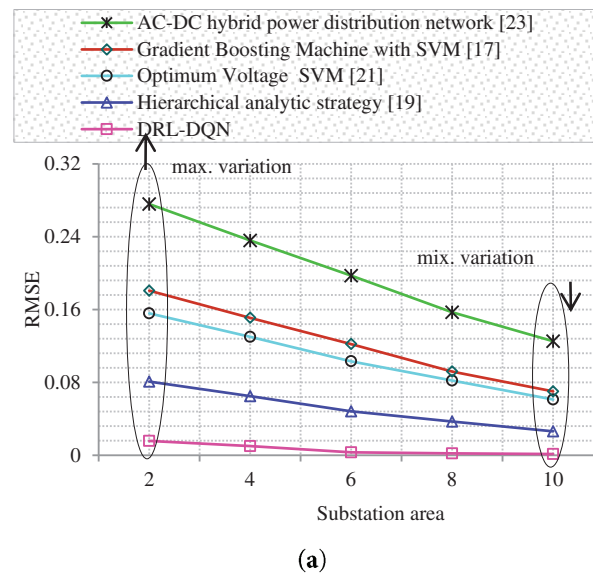
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Table 4 (continued)

Hyperparameter	Value
exploration	initial_epsilon = 0.4 final_epsilon = 1/2016 epsilon_timesteps = 100,000
model_fcnet_activation	Relu
num_agents	5

Results

This section examines how well the suggested method worked. To start, we will go over the training step and the outcomes for a few agents. Second, we provide an assessment of agent testing based on one hundred previously unknown cases. The testing procedure is detailed to show that the power network's performance is substantially enhanced when the suggested RL agent is used for control. To validate the merits of the suggested method, we compare the outcomes to those of agents that are comparable in the literature. Finally, the results of using the suggested agent are shown. Finally, the algorithm's shortcomings are detailed, which is given [Fig. 4](#).

**Figure 4: (Continued)**

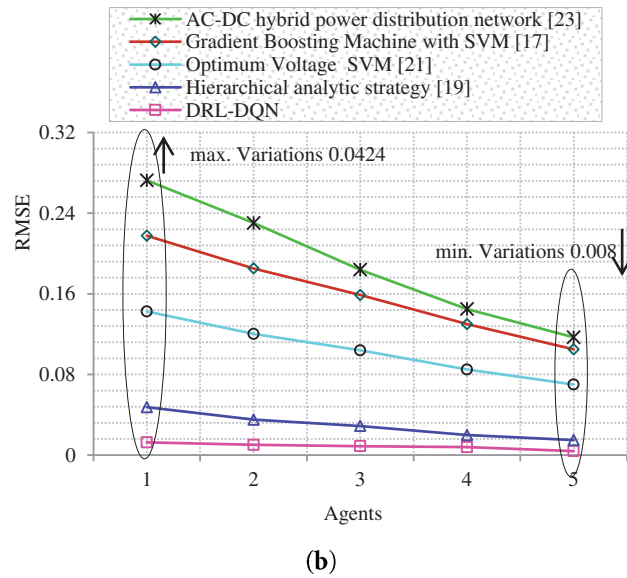


Figure 4: RMSE analysis (a) Substation area and (b) Agents [17,19,21,23]

Maintaining control of the grid from one beginning point to another is the objective of each episode, which includes observations, actions, and rewards. We trained using a dataset for the IEEE 33-bus system that has been used in earlier research, which has 800 scenarios, which is depicted in Figs. 4–6. We begin by displaying the DRL-DQN training curve. The agent was trained with 60,000 iterations in DRL-DQN, as previously stated. Fig. 7 depicts the agent's improving process. Fig. 7 shows that the cumulative prize in each episode grew substantially as the iteration count rose. In addition, the agent learnt faster in the start, and the trend of increasing performance tended to slow down as training progressed, as is the case with most current DRL systems. It is clear that the payout was rather consistent until about episode 200.

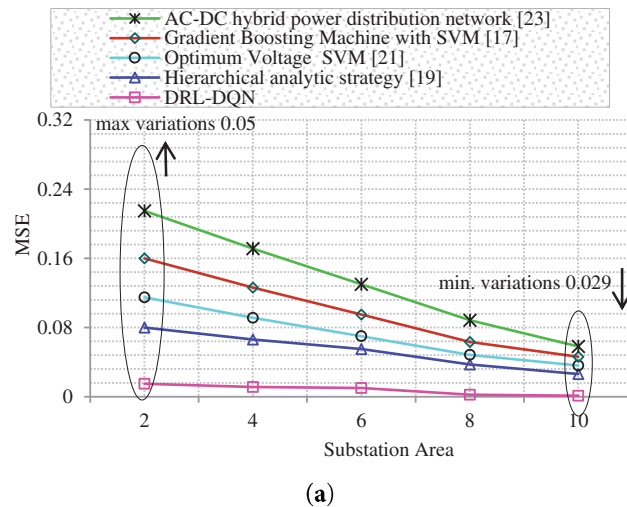


Figure 5: (Continued)

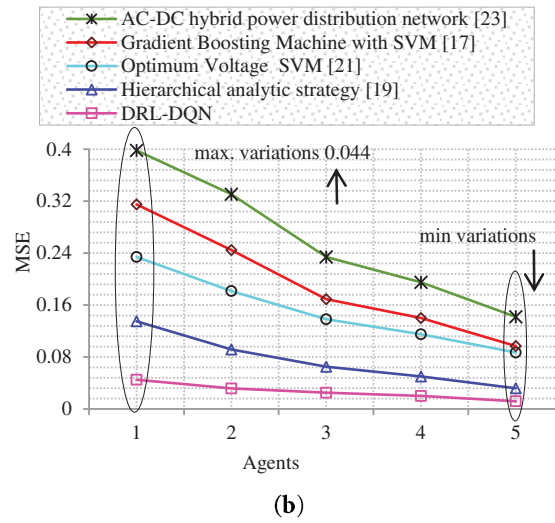


Figure 5: MSE analysis (a) Substation area and (b) Agents [17,19,21,23]

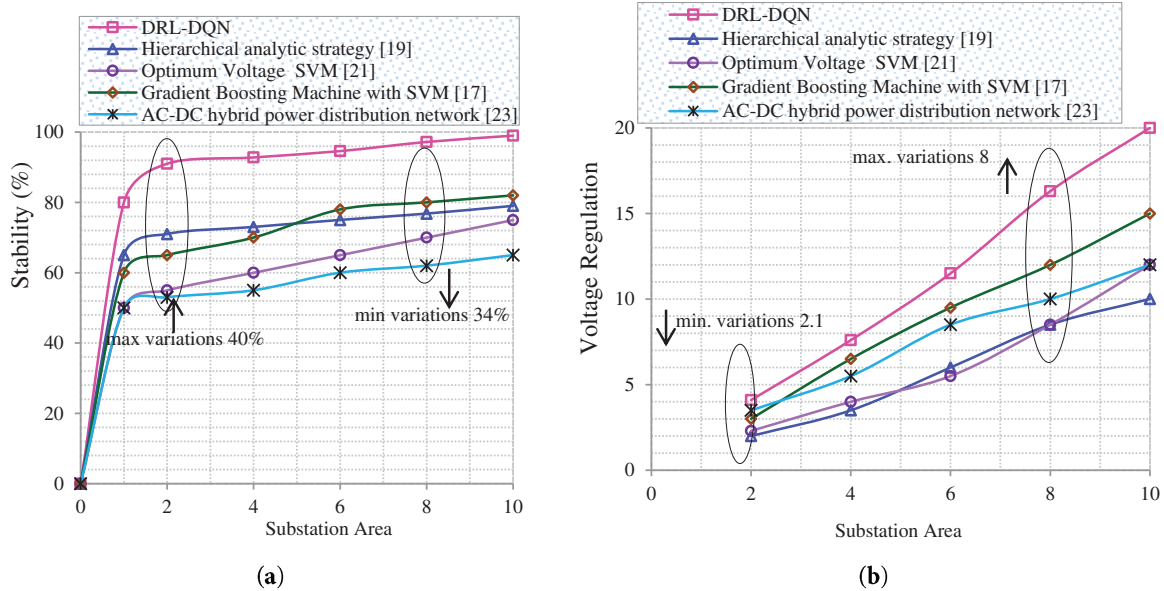


Figure 6: (a) Network stability analysis and (b) Voltage regulation analysis [17,19,21,23]

In order to teach the agent to retain the power network under its control for as long as possible, it is necessary to monitor the average length of events. When the agent reaches a suitable performance level during training, the training may be terminated via early stopping. The algorithm's simplicity and the discrete structure of the observation with action space types led to the selection of DQN with its derivatives for study. We find the DQN algorithms that were used in this study in the Rllib package. We continued our analysis using DDDQN and prioritized replay since it demonstrated the highest performance. In order to avoid smart grid blackouts and cascade failures, the suggested DRL agent took charge of the grid by figuring out the best approach to set up the electricity network at the start of the episode. After learning that the default topology is suboptimal, the agent was able to select the optimum topology by combining steps 3 and 5. There is a much shorter series of decision-making steps in distressing conditions, therefore setting optimum

topology at the beginning of the episodes makes power system control considerably simpler. Only changes to the substation's configuration are taken into account by this method, which is part of system-level control. Regulation actions, implemented by the control system, are used to manage power flows across transmission lines, ensuring proper voltage, current, and load distribution under normal operating conditions.

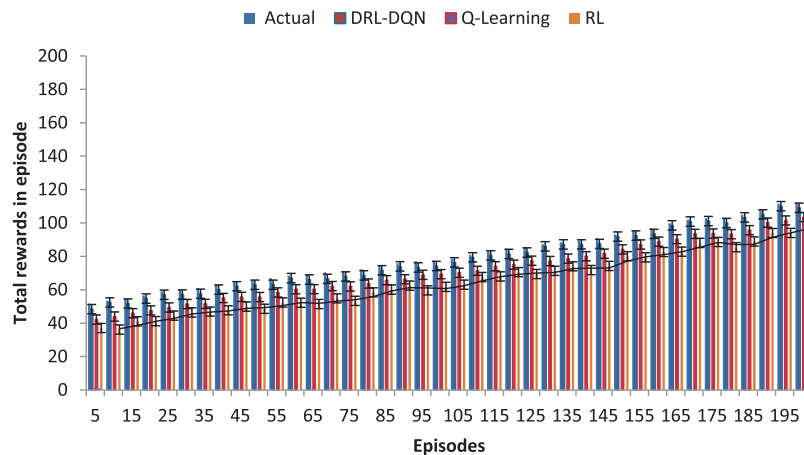


Figure 7: Rewards (total) during Episodes

6 Conclusion

The strategic answer for converting traditional MV/LV networks into intelligent, robust, and future-ready grids is provided by flexible interconnection devices. Their implementation is essential for supporting electrification objectives, facilitating effective DER integration, and guaranteeing dependable electricity supply in the face of increasing demand and unpredictability. This study examined FID establishing multi-substation distribution systems in metropolitan load-centered cities in detail, with an emphasis on the needs of electric power companies in promoting and developing FID and its uses. The voltage, system capacity, and equipment of two different systems were detailed. There were five power functions and three use scenarios that were detailed. The power functions of a multi-substation distribution network layout were explored, and the specific needs of load-centered cities were considered, in relation to distribution network interconnect retrofits. New DQN features for high-power-density power converter architectures are the focus of this research. The operating modes and benefits were proven by an MATLAB simulation of a 10 kV four-substation transmission line using FID. The model showed that the system was more stable, efficient, and reliable. The report also covered the opportunities and threats from several angles to help with the development as well as commercialization of FID in real-world distribution system linkages. Development of multiport DCT devices, configuration of effective protection schemes, application of new control strategies at both the converter while system levels, exploration of centralized training while decentralized execution frameworks, universal design methodologies, and the establishment of technical standards were all part of this. In the future, this study is extended into the following aspects:

- Integration of artificial intelligence and machine learning for problem diagnosis and predictive control
- Planning and operation of the grid via the use of digital twins
- The implementation of FIDs requires both standardization and regulatory frameworks.
- Architectures that operate on plug-and-play for scalability

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