Review of Microgrids and Associated Protective Systems

Abstract: Historically, the human appetite for electrical energy has never been higher than it is currently. This high demand for electricity has driven need for generation of power to a record high. The current power network is therefore challenged with the need for quality, reliable and sustainable power generation, transmission and distribution. The network, in most countries, is aging – requiring higher resources to meet contemporary challenges, coupled with the need to minimize power losses and optimize power production. These challenges have necessitated innovative power production techniques, such as the microgrid. The operation of microgrid comes with emerging challenges. In this paper, some of the most obvious challenges of utility and microgrid operations have been articulated and thoroughly reviewed. The paper also presents some of the recent proposals for microgrid protection, as well as the limitations associated with these proposals.

Comment [E61]: What do you mean here?

Keywords: Microgrid, Protection, Distributed Generation

1 Introduction and Motivation

Concerns for primary energy availability and aging infrastructure of current electrical generation, transmission and distribution networks are challenging security, reliability and quality of power supply system. To improve the power supply, distribution grids are being transformed from passive to active networks to [1]:

- Facilitate access to distributed generation (DG).
- Enable local energy demand management, interacting with end-users through smart metering systems.
- Apply the transmission technologies such as dynamic control techniques to the distribution grid, to ensure a higher overall level of power security, quality and reliability.

Comment [E62]: Put all these in a paragraph together

A microgrid is a power system which comprises of small (micro-), distributed generators, energy storage systems and controllable loads operated as a single controlled and coordinated unit such that it could operate in a grid-connected or autonomous (islanded) mode [2]. The primary interest of microgrid is supply of quality, reliable and sustainable power to a local load, resulting in need for bidirectional power flow. This is contrary to the main purpose of DG which focuses on increasing unidirectional availability of power without focusing on the satisfaction of a local load. Fig. 1 depicts a simplified architecture of a typical microgrid connected to the utility at the Point of Common Coupling (PCC).

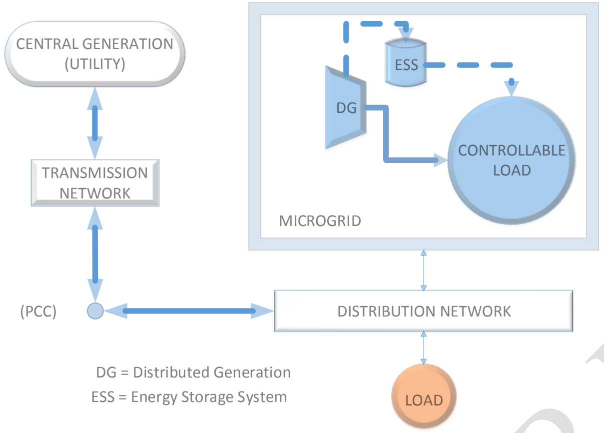


Fig. 1. A simplified utility-microgrid architecture

There are numerous research efforts aimed at full scale deployment of microgrids. These efforts are largely driven by governments and corporate bodies, resulting in classified research data and findings. This paper attempts to present an up to date results of research efforts in microgrid protection systems.

2 Current Power System and Its Challenges

In the contemporary power system, bulk energy production starts from centralized large generating systems. The power generated is then transmitted, mostly over long distances, to the distribution network where the energy is consumed. The distribution network is a low voltage or medium voltage network and radial in nature. Abnormal conditions such as faults could occur at various stages of the system, necessitating incorporation of control and protective devices in the network. The transmission network links the distribution network (consumer end) to the generation (producer end), but introduces power losses which results in economic loss to the utility and poor quality supply to the consumer [3], [4], [5]. Increasing energy demand and need for sustainable power generation drive growing penetration of renewable energy resources in form of microgrid. The increasing penetration of distributed generation changes the natural topology of the distribution network from radial to mesh or ring [6], [7], [8], [9], [10]. Consequently, the LV distribution network can no longer be considered a passive appendage to the transmission network – it becomes an active distribution network; a distributed generation. The impact of DGs on power balance and grid frequency may become obvious in the future [4]. This topology change, converter-interfacing of microsources based on power electronics (PE) and the imminent bidirectional power flow render the contemporary protective devices such as overcurrent relays (OCRs) inappropriate for optimal system operation, particularly under various control strategies and operating modes [1, 3, 11].

In general, the protection problems can be divided into two categories:

- Fault detection problems.
- Selectivity problems.

2.1 Blinding of Protection

This is a fault detection problem. Connection of DG not only alters the load flow in the distribution grid but can also alter the fault current during a grid disturbance. Most distribution grid protective systems detect an abnormal grid situation by discriminating a fault current from the normal load current. Because DG changes the grid contribution to the fault current, the operation of the protective system can be affected [10], [12], [1], [13], [14], [15], [16], see fig. 2.

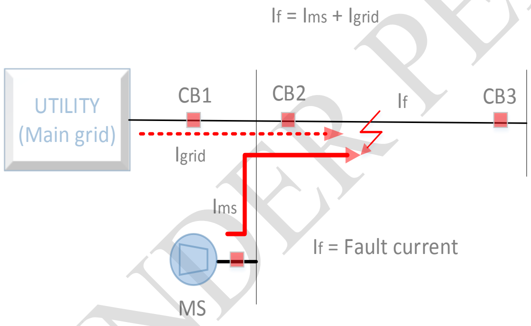
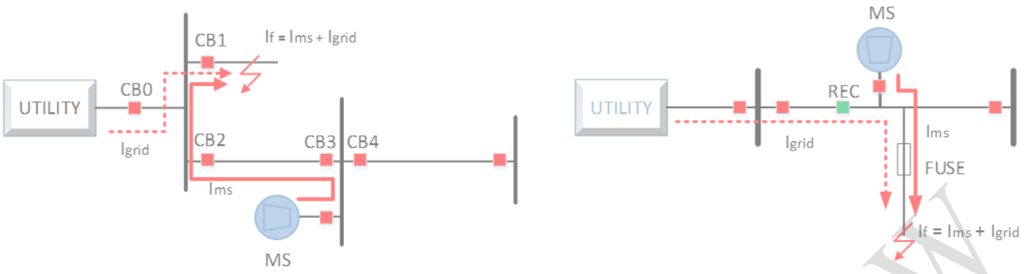


Fig. 2. Blinding effect of MS on CB1

2.2 Sympathetic Tripping

Sympathetic tripping, also termed false tripping, is a selectivity problem and occurs when a generator installed on a feeder contributes to the fault in an adjacent feeder connected to the same substation [15], [17], [18], [19], see fig. 3a.



a b

Fig.3. Typical challenges associated with use of OCRs in distributed generation

a. Sympathetic tripping

b. Loss of fuse-recloser coordination

2.3 Loss of Fuse-Recloser Coordination

Protection of overhead distribution feeders with automatic reclosers is a very efficient way to protect against temporary disturbances and minimize the number of supply interruptions. Coordination between the reclosers and the lateral fuses enables permanent faults to be cleared in a selective way. Connection of DG to distribution feeders with automatic reclosers causes several protection problems. The fault current detection by the recloser is affected by the generator contribution and can lead to a detection problem. The coordination between reclosers or fuse and recloser can be lost which directly causes selectivity problem [20], [21], [22], [23], see fig. 3b. This is a selectivity problem.

Other problems associated with use of overcurrent relays (OCRs) in microgrid include:

- Islanding and Non-Synchronized Reclosing.
- Disabling of automatic reclosing.

3 Microgrids and Future Power Systems

The ever-increasing human appetite for electric power, changes in regulatory and operational climates of contemporary electric utilities, and the evolution of small generating units – including photovoltaic, microturbines, fuel cells, and internal combustion engines have opened new opportunities for electricity users to generate power at their premises. This makes distributed generation (small power generators usually located at sites where the energy they generate is consumed) a promising option to meet growing customer needs for economic and reliable electric power. This could make a consumer to become a net producer of electricity. Organizing these distributed energy resources (generators, energy storage and controllable loads) into a microgrid has the potential to meet environmental, regulatory, customer and utility needs. Some of the features of microgrid that make it promising as a solution to the challenges of meeting the foreseeable future energy demand include:

- High reliability – providing quality power to consumers.
- Potential for “plug and play” – addition of energy resources to the microgrid is flexible.
- Capacity for seamless islanding – this helps ensure supply continuity in the event of fault on the utility [24].

A microgrid is a “building block of smart grids” [25]. A microgrid could be ac, dc or hybrid. It is essentially a conversion of the passive distribution network to an active network. An active distribution network facilitates distributed decision-making and control, and the power flows are bidirectional in the network, in contrast to contemporary power system where power flow is unidirectional. It eases the integration of DG, RES, demand side integration (DSI) and energy storage technologies. It also enables use of intelligent electronic devices (IED) and controllers, which conform to common client-server protocol-based communication services based on uniform standards. The main functionality of a microgrid is to efficiently link power generation with consumer demands, allowing both to decide how best to operate in real-time [2-4].

It is a cluster of interconnected DGs, loads and intermediate energy storage units that co-operate with each other to be collectively treated by the grid as a controllable load or generator. It is connected to the grid at only one point, the point of common coupling (PCC), see fig. 1. DGs are connected to the distribution networks, mainly at medium voltage (MV) and low voltage (LV) levels. DGs include microsources (microgenerators) such as microturbines, fuel-cells and photovoltaic (PV) arrays together with storage devices, such as flywheels, energy capacitors, batteries and controllable loads e.g. electric vehicles [4].

4 Challenges of Microgrid Operation

One of the main challenges faced in microgrid operation is associated with the huge difference between the fault current level in the grid-connected mode and the autonomous mode [26], occasioned by the fact that the short circuit levels of converter-interfaced microsources are limited to about 2-3 times their rated capacities by their controllers [27]. Also, in a microgrid the control strategy such as P or Q control dictates the values of critical network parameters such as current magnitudes, voltage magnitudes and angles. When the microgrid is grid-connected, the control is dictated by the grid; when it is in autonomous mode of operation, its control is dictated by its operating conditions and operational codes. For the same fault condition, the fault current or other parameters could differ under different control strategies. Some of the challenges limiting full scale deployment of microgrids include:

1. Design of protection systems – due to:
    - Bidirectional power flow.
    - Network topology change - meshed network.
    - Converter interfacing – PE interfaced microsources incorporate controllers which are current limiters, even during system stress.
2. Voltage and frequency control strategies – power electronics (PE).
3. Reliable stand-alone mode of operation – lack of rotating inertia in PE interfaced microsources (MSs), resulting in poor transient stability during disturbances. This results in inability to meet Low Voltage Ride Through (LVRT) and other grid codes.
4. Seamless transition from islanded mode to grid-connected mode and vice versa – disconnection and reconnection provoke voltage fluctuation and frequency oscillations.
5. Seamless integration – plug and play, and peer-to-peer.
6. Uncertainty in dispatch and reserves – intermittent nature of primary energy source and high cost of large storage systems [2, 28].

5 Microgrid Protection Systems in Literature

Fig. 4 presents a graphical view of the basic quantities associated with different protective systems for microgrids.

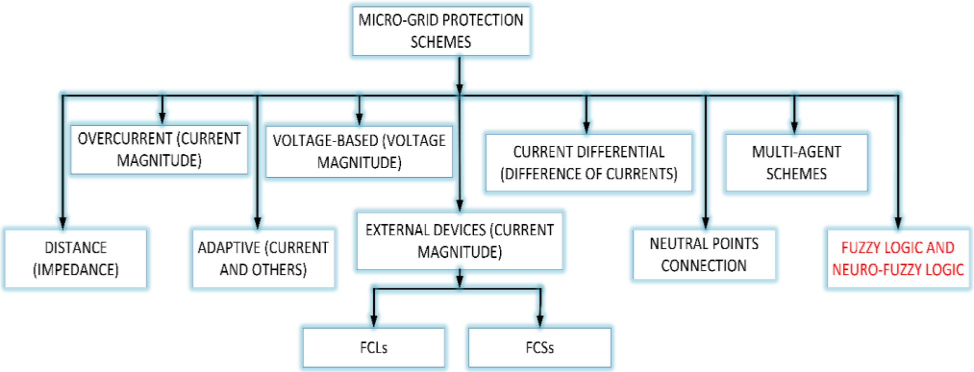


Fig. 4. Block diagram showing the current state of microgrid protection schemes in literature

5.1 Overcurrent Protection Schemes

Proposals for microgrid protection based on current magnitudes evolved from the well-established overcurrent (OC) protection in the utility industry. Such proposals attempt to solve the problem of relay blinding caused by increased penetration of PE interfaced microsources in grid-connected mode by making modified measurement of current magnitude or by adding measurement of other quantities to improve device's reliability. A typical example is the approach proposed by Nikkhajoei and Lasseter [29, 30] in 2006. Their proposed technique was based on measurement of zero and negative sequence quantities to distinguish between line-to-ground and line-to-line faults respectively. In 2008, Best et al [31] implemented a 3-stage selectivity scheme. In their technique, stage 1 detects the fault event in accordance with local measurements; stage 2 deploys inter-breaker communication; and stage 3 adapts relay settings via a supervisory controller. In 2012, Zamani et al [32] developed a novel protection scheme using micro- processor based relays for low-voltage microgrids protection against types of faults in both autonomous and non-autonomous modes of operation. Its operation was based on definite-time grading of all relays within the microgrid, requiring use of communication links. These proposals based on overcurrent protection suffer from either blinding or vulnerability to communication failures, rendering them unreliable.

5.2 Voltage-Based Protection Schemes

Voltage-based protection schemes basically employ voltage measurements in protecting the microgrids against different kinds of faults. In 2006, Al-Nasseri et al. [33] proposed a scheme that could monitor and transform output voltages of microsources into dc quantities using the d-q reference frame such that the scheme could be employed in protecting the microgrids against both in-zone and out-of-zone faults. In 2009, a novel protection scheme was proposed by Loix et al. [34]. The scheme is based on the effect of different fault types on Park's components of voltage and it is capable of protecting microgrids against three phase, two phase and one phase-to-earth faults. Its primary operation is independent of communication links, but requires communication links for optimal protection. The most prominent feature of this scheme compared to the one proposed by Al-Nasseri et al. [33] is its versatility – it could be used in the protection of microgrids of various configurations.

5.3 Current Differential Protection Schemes

A form of protection for apparatus such as transformers, generators, busses and power lines and feeders is current differential. A differential relay works on the basic theory of Kirchhoff's current law, which states that the sum of the currents entering and exiting a node equals zero [35]. It operates only when the differential between these currents exceeds a pre-determined magnitude. A major strength of this scheme is its insensitivity to bidirectional power flows and reduction in fault current magnitudes in islanded microgrids. In 2006, Nikkhajoei and Lasseter [30] proposed a dual technique scheme for microgrid protection by differential protection and symmetrical components calculations. They employed zero sequence and negative sequence currents within the microgrid to detect Single Line-to-Ground (SLG) and Line-to-Line (LL) Faults, respectively. In 2006, Zeineldin et al. [36] published a paper on the microgrids future and were concerned on two major challenges, voltage/frequency control and protection. Consequently, they proposed a scheme where they had employed differential relays in both ends of each line. These relays which were designed to operate in 50ms were capable of protecting the microgrid in both grid-connected and autonomous operation modes. In 2009, Conti et al [37] detailed out a scheme based on three protection strategies in detection of phase-to-ground faults in isolated neutral microgrids. In 2010, Sortomme et al. [38] proposed a novel protection scheme based on the principle of synchronized phasor measurements and microprocessor relays in order to recognize all kinds of faults including High Impedance Faults (HIFs). They showed that installing the relays at the end of each microgrid line will provide a robust protection. In 2010, Parsai et al. [39] proposed a communication-based scheme called Power Line Carrier (PLC) with multiple levels of protection offering effective protection for meshed microgrids. In 2011, a novel scheme was proposed by Dewadasa et al. [40] using differential protection. This scheme takes into account all the protection challenges such as bidirectional power flow and reduction of fault current level in the islanded operation mode and it is capable of protecting the microgrids in both grid-connected and islanded modes of operation. A major contribution of this scheme is that it could potentially satisfactorily protect feeders and microsources within the microgrid.

5.4 Distance (Impedance) Protection Schemes

A distance relay (also called impedance relay) differs in principle from other forms of protection because its performance is not governed by the magnitude of the current or voltage in the protected circuit but rather on the ratio of these two quantities. Such relays are actually double actuating quantity relays with one coil energized by voltage and other coil by current. The current element produces a positive or pick up torque while the voltage element produces a negative or reset torque. The relay operates only when the V/I (impedance) ratio falls below a predetermined value (or set value). In 2008, Celli et al [41] proposed a distance relay scheme to detect grounded faults in distribution systems with high penetration of distributed generation. This method uses wavelet coefficients of the transient fault current at critical points of the network. The scheme works without communication link or synchronized measures. However, if ICT is used to permit communication among the relays, the scheme could be used to satisfactorily protect the network against ungrounded faults.

5.5 Adaptive Protection Schemes

Adaptive protection scheme could solve problems arising from both modes of grid connected and islanded operations. In adaptive protection, automatic readjustment of relay settings triggers when the microgrid changes from the grid connected mode to the islanded mode or vice versa. It is an online system that could modify the preferred protective response to change under system conditions or requirements in a timely manner through external generated signals or control actions.

In 2006, Tumilty et al [42] suggested an adaptive protection scheme without the requirement of a communication system. They used a voltage-based fault detection method in discriminating the voltage drop in short-circuit incidents and over-load events. In 2009, Oudalov and Fidigatti [43] proposed a novel adaptive microgrid scheme using digital relaying and advanced communication. The system is based on a centralized architecture which determines the microgrid state and adapts protection settings accordingly. In 2011, Dang et al [44] employed Energy Storage (ES) and isolation transformers to detect the operating mode of microgrid. Therefore, identification of the fault could be executed by comparing between the zero-sequence current and a pre-determined value. In 2012, Khederzadeh [45] published a proposal in which the potential of the numerical relays was efficiently used to protect the microgrids. In this scheme, settings of the relays are adapted to the status of the microgrid, i.e., utility grid-connected or autonomous operation.

5.6 Protection Schemes Driven by External Devices

As stated in 4, the main challenge faced in microgrid protection is associated with the huge difference between the fault current levels in the grid-connected mode and the autonomous mode [26]. Consequently, it becomes to implement an adequate protection scheme which is able to operate suitably in both grid-connected and autonomous modes. Some approaches in literature propose a modification of the short-circuit level when the microgrid operating mode changes from grid-connected to autonomous, or vice versa. These devices can be classified into the following two groups:

5.6.1 Fault Current Limiters (FCLs): FCLs are employed to reduce the aggregated contribution of all distributed generation units, and it is capable of adequately changing the short circuit current level to exceed the design limit of different equipment components. In 2011, Ustun et al. [46] proposed a conceptual design of a microgrid protection scheme using current limiters in fault current estimation. The proposed scheme requires communication link to monitor the microgrid and update relay fault currents according to the variations in the system. It is designed such that it responds to dynamic changes in the system such as the connection/disconnection of DGs**.** In 2012, Ghanbari and Farjah [47] proposed a novel FCL scheme using resonant type solid-state fault current limiter (SSFCL) which exhibits very low impedance through a series resonant circuit under normal condition. Under fault condition, the fault current limiter offers a very high impedance through a parallel resonant circuit. In 2013, Ghanbari and Farjah [48] proposed a unidirectional fault current limiter (UFCL). The proposed UFCL is installed between the upstream and downstream network, such that it only limits the current contribution of the downstream network during a fault in the upstream. Inversely, during a fault in downstream, the UFCL is inactive and allows a full contribution of the upstream network. It was shown that by this strategy, the proposed UFCL can preserve the coordination protection of the upstream over-current relays.

5.6.2 Fault Current Sources (FCSs): As stated in 4, the short circuit current level in the microgrid is limited to approximately 2-3 times of the rated current because of the existence of inverter-based DGs, fault current sources in the form of energy storage devices (flywheels or batteries) can be used to provide supplementary short-circuit level to the network [26]. In 2013, Oudalov et al. [1] proposed a FCS for microgrid protection. During normal operation, the FCS power circuit remains idle. Upon fault occurrence, the network voltage drops, activating the FCS. The FCS attempts to restore the original network voltage by injecting a fault current into the network. The injected fault current is sufficiently high to trigger OC relay trip logic, energizing a circuit breaker.

5.7 Protection Based on Multi-agent Schemes

In 2016, Hussain et al. [49] proposed an N-version programming-based protection scheme for micro-grids using multi-agent approach. The scheme was developed in MATLAB Simulink with three protection versions namely, Clarke's transformation-based current protection, positive sequence phase differential-based protection and conventional over-current-based protection. In their proposal, the software makes the final decision about the fault and which of the three protection versions to activate through a polling process. The polling process relies on a truth table and a K-map for voting and making of decision. Their proposal is applicable to both balanced and unbalanced faults in both modes of operation. However, its drawbacks include its reliance on inter-agent communication which makes the system vulnerable to communication failure and highly expensive to operate. In addition, the entire proposal is capital intensive since it uses three different hardware for fault detection and fault clearance. It includes two non-over-current networks in addition to the over-current protection found in conventional schemes, this results in over-redundancy of hardware and increased failure points.

5.8 Protection Based on Neutral Points Connection

In 2016, Kamel, Alsaffar and Habib [50] proposed a simple and novel protection scheme for islanded micro-grids. Their proposal simply increases the magnitude of fault current in islanded mode of operation such that the fault current from the inverter is sufficiently large and sustained for detection using conventional over-current devices for protection. The proposed scheme achieves this by connecting the neutral points of all micro-grid loads to the neutral line of the micro-grid's earth. By providing a path of least resistance, this increases the short circuit current during short circuit fault. The proposed scheme is simple, cost-effective and reliable. It also satisfies the peer-to-peer requirement of micro-grid. However, it fails the plug-and-play requirement of micro-grid. Its applicability is also limited to micro-grids in islanded mode of operation. For a micro-grid that is capable of grid connection, the proposed scheme is unreliable and inappropriate. This is because, under utility short circuit the proposed protection could become counter-productive and hazardous to other equipment and personnel when subjected to utility short circuit MVA.

5.9 Protection Based on Fuzzy Logic and Neuro-Fuzzy Logic

In 2018, Maruf [51] proposed a multi-variable relay based on combination of fuzzy rules. The relay consists of two sub-relays: feeder sub-relay and micro-source sub-relay. The feeder sub-relay measures four parameters (active power, reactive power, voltage and current) of the feeder while the micro-source sub-relay measures similar parameters of the micro-source. Offline and online response tests of the proposed relay show that it generates logic 1 during short circuits and logic 0 during normal operating conditions in both grid-connected and islanded modes of operation of the micro-grid. The proposed relay also provides equivalent response under both voltage and reactive power control strategies. This is consistent with response of a reliable protective relay as reported in related literature. The proposed relay also supports plug-and-play and peer-to-peer requirements of micro-grids. Similar to digital relays reported in literature, the proposed relay is a departure from classical relays wherein protection is based on threshold of short circuit current. In the proposed relay, protection is based on nominal parameters of micro-sources and feeders.

6 Merits and Demerits of Protection Systems in Literature

Table 1 shows the strength and weaknesses associated with the proposals for microgrid protection in literature.

Table 1 Merits and Demerits of Proposals for Micro-grid Protection in Literature

Basic Measurement in Proposal	**Merits**	**Demerits**
Current magnitude	Effective for both short-circuit and high impedance faults	Blinding of OCRs
Voltage magnitude	Blinding of OCRs/Effective for in-zone and out-of-zone faults	Vulnerable to communication failures
Current differential	Very effective for micro-grids protection of various faults	Very expensive and vulnerable to communication failures
Distance (Impedance)	Operation may not require communication links	Intermediate in-feed of microsources has impact on the measurement of the fault impedance
Essentially current, but other quantities could be employed	Adapts to changes in network configuration	Vulnerable to communication failures and adaptation may not be instantaneous
Current - Use of external devices	Effective for both grid-connected and autonomous operating modes	Expensive and potentially counter-productive
Multi-agent approach	Applicable to both balanced and unbalanced faults in both modes of operation.	Over-redundancy of hardware and increased failure points.

Neutral points connection	Simple, cost-effective and reliable. It also satisfies the peer-to-peer requirement of micro-grid	It fails the plug-and-play requirement of micro-grid. Its applicability is also limited to micro-grids in islanded mode of operation
Fuzzy Logic	Applicable to both balanced and unbalanced faults in both modes of operation	Rules have to be formulated to meet requirements of each micro-grid, resulting in programming of hardware for specific micro-grid

7 Conclusion

This paper has articulated the challenges of the utility power system and the drivers for innovative power system, such as the microgrid. It has also thoroughly discussed the obvious operational challenges of the microgrid, particularly with respect to protection. A summary of the various categories of proposals to the protection of microgrids in literature as well as the deficiencies of each category of proposal has also been presented in this work. The aim of this study, which was to conduct an overview on microgrids and associated protective systems, has been achieved.

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