Enhanced Voltage Relay for AC Microgrid Protection

G. P. Santos, A. Tsutsumi, J. C. M. Vieira

***Abstract*-- Microgrids emerged as an efficient way to integrate distributed energy resources and local loads into power distribution systems, allowing the local system operation in grid-connected and islanded modes. However, the microgrids imply several challenges for the protection systems, such as the changes in fault current path and the decrease of the fault current amplitude during islanded operation. Therefore, conventional overcurrent protection does not guarantee selectivity, coordination, reliability, and adequate trip time in AC microgrids. Under this perspective, voltage-based relays have been widely investigated as a potential protection for AC microgrids. Thus, this paper critically reviews voltage-based protection and proposes improvements to an existing technique, aiming to simplify the settings and guarantee reliability and selectivity among various voltage-based protection devices. The results showed that our modifications improved the selectivity and reliability of the voltage-based protection compared with the original technique and the traditional overcurrent protection devices for different topologies of an AC microgrid.**

***Keywords*: distributed energy resources, distributed generation, power distribution faults, microgrid, protection system, voltage-based relays.**

I. Introduction

In recent years, there has been an increased concern about the availability of electricity, power quality issues, and the environmental impacts of traditional energy sources. Thus, there was an increase in Distributed Energy Resources (DERs), mainly renewable sources. In this context, the concept of Microgrids (MGs) emerges to maximize the benefits observed by the connection of DERs to the system [1]. According to [2], an electrical system can be considered a microgrid if it has well-defined electrical boundaries, a control system to manage and dispatch resources as a controllable entity, and a distributed generator capacity exceeding the demand of critical loads, so it can operate in islanded mode and supply the local loads. Internally, MGs are complex and can have different types of distributed generators and energy storage systems. However, from the distribution system perspective, the MG can be treated as a single controllable entity since it can operate by consuming or injecting power into the grid [3].

There are no precise requirements for MGs, such as the type or capacity of DERs. Anyhow, distributed generation can supply at least part of the local loads' demand, allowing MGs to operate either grid-connected or islanded. A typical MG is connected to the grid through the Point of Common Coupling (PCC), which could benefit the electric power systems and consumers, increasing the system's reliability and reducing the assets and losses of the transmission system. However, the MGs' protection and control systems are challenging. So, several studies aimed to improve the protection systems and adapt to the new operating conditions of MGs [4], [5], [6].

An MG could have several DERs connected and change its configuration with the connection or disconnection of sources, modifying the fault current path and amplitude. Besides, the different types of DERs also can change the fault currents and create bidirectional power flow. For example, the rotating machine-based DERs, connected directly to the grid, have high fault currents, whereas inverter-based DERs have a limited contribution to the fault current. Besides, the fault current reduces drastically on the MG islanded operation because there is only the contribution from the distributed generation. These MG operation modes challenge the conventional overcurrent protection of distribution systems since the amplitude and direction of fault current depend on the capacity and type of DERs, and the variation of the MG operation (grid-connected or islanded).

Thus, conventional overcurrent protection may not be suitable for MGs. Likewise, the islanded MG has lower fault currents than the grid-connected mode, which could not reach the current pickup value of the conventional overcurrent protection defined in grid-connected scenarios. In this context, the authors in [7] discuss the performance of commercial relays in several MG scenarios, assessing the protection selectivity and coordination. According to the authors, the commercial relays failed to detect the short circuit or incorrectly determined the fault current direction.

Several authors proposed new protection strategies for digital relays to overcome this issue, including voltage-based methods. In [8], the authors studied the voltage-based protection system using the transform ABC-dq rotating system, representing the voltage disturbances in a continuous signal. This strategy is independent of the fault current amplitude, turning it suitable for islanded MG with high insertion of inverter-based distributed generation and effective for fault detection. However, the microgrid analyzed has only one bus, and the protection system needs communication, which makes the method costly. The authors in [9] implement a communication-based protection system with overcurrent, under/overvoltage, and differential relays. The strategy proves

This work was supported by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brazil (CAPES) - Finance Code 001 and by the São Paulo Research Foundation (FAPESP), Grant Nº 2021/04872-9. G. P. Santos, A. Tsutsumi and J. C. M. Vieira are affiliated with the Department of Electrical and Computer Engineering, São Carlos School of Engineering, University of São Paulo (USP), SP, Brazil (e-mail:gabriella.pinheiro.santos@usp.br, amandatsutsumi@usp.br and jcarlos@sc.usp.br).
Paper submitted to the International Conference on Power Systems Transients (IPST2023) in Thessaloniki, Greece, June 12-15, 2023.

to be effective for several MG operating scenarios and topologies, including high impedance faults. However, the proposed protection needs to connect a relay on each feeder section and a communication system, making this method costly and vulnerable to communication failures.

In [10], the authors proposed a voltage-based relay that operates due to changes in the values of the symmetrical components. The positive sequence voltage is defined as the reference of the method, with a fixed value of the pre-fault voltage bus. In contrast, the negative and zero sequences have their value changed. The strategy proves to be effective for fault detection, but it depends on the MG topology. The authors in [11] applied voltage-controlled overcurrent relays, which proved to be effective for two-phase faults but failed for the three-phase type due to the variation of the fault current amplitude. The authors in [12] propose a new time-voltage-based relay tripping characteristic for directional overcurrent relays to ensure protection system coordination. This method guarantees coordination with a lower trip time than the conventional methods. However, the study only considered a fixed MG topology, and the proposed relay may need to be adjusted for changes in the topology or the DERs connection. In [13], a voltage-based method is proposed depending entirely on local measurements, independent of communication systems. This method was compared with the method proposed in [12], obtaining promising results as the previous study, with lower trip times. However, the relay current settings depend on prior knowledge about the distributed generation arrangements of the MG. So, unexpected changes in the MG topology can undermine the technique's performance.

In [14], the same authors of [13] presented a more straightforward method as a function of the short circuit voltage without previous knowledge of the DERs connected to the grid. A relay starter element is responsible for detecting the fault by identifying undervoltage, overcurrent, or high-impedance faults events. This method presented promising results, maintaining coordination and selectivity under any tested fault conditions. However, the risks of sympathetic trips are very high because the voltage relays installed at adjacent feeders are subjected to very similar undervoltages during short circuits, which may cause the disconnection of healthy feeders due to faults on the other feeders. Hence, the proposed voltage-based protection does not guarantee the protection security. The method proposed in [15] adapts the pickup current as a function of the positive sequence voltage, showing a selective and coordinated protection method. However, it is still necessary to evaluate the protection for islanded microgrids, which present low variation of fault voltage for different buses and may impact the definition of the pickup current.

Table I indicates the main characteristics of studies on voltage-based protection applied to MGs. In the fourteen studies, only [11], [16], and [17] addressed an MG considering an energy storage system, inverter-based generators, and the rotating machine as DERs. However, [11] does not evaluate the protection coordination, and [16] and [17] are communication-based protection methods, which are more costly and vulnerable to cyberattacks. Besides, all studies reviewed do not present a detailed analysis of the dependability and security of the proposed protection.

This paper proposes essential modifications in the settings definition and the relay starter to improve and simplify the voltage-based relay presented in [14], increasing the protection selectivity and reliability. The main contributions of this paper are an enhanced version of the voltage-based relay and comprehensive tests to evaluate the dependability and security of the method, which are not analyzed in [14]. Moreover, a comparative study of conventional overcurrent and voltage-based methods is presented to validate the reliability improvement of the enhanced voltage-based protection.

TABLE I
MAIN CHARACTERISTICS OF VOLTAGE-BASED PROTECTION STUDIES

Reference	Distributed Energy Resources			COORD	COM	ADPT
	RMDG	IDG	ESS			
Al-Nasseri et al (2006) [8]	✓	✓	-	-	✓	-
Sortomme et al (2010) [9]	✓	✓	-	-	✓	-
Wang et al (2011) [10]	-	✓	✓	-	✓	-
Ma et al (2013) [18]	✓	-	-	-	✓	✓
Wang et al (2014) [11]	✓	✓	✓	-	-	-
Saleh et al (2015) [12]	✓	✓	-	✓	-	-
Jamali and Borhani-Bahabadi (2017) [13]	✓	-	-	✓	-	-
Núñez- Mata et al (2018) [16]	✓	✓	✓	✓	✓	✓
Jamali and Borhani-Bahabadi (2019) [14]	Not specified			✓	-	✓
Mishra et al (2020) [15]	✓	✓	-	✓	-	-
Ranjbar et al (2020) [19]	✓	✓	-	-	✓	-
Mohanty et al (2020) [20]	-	✓	✓	✓	-	✓
Ebrahimi et al (2022) [21]	-	✓	✓	✓	-	✓
Hoang et al (2022) [17]	✓	✓	✓	✓	✓	✓
Enhanced Method	✓	✓	✓	✓	-	✓

RMDG - Rotating Machine Distributed Generator; IDG - Inverter-based Distributed Generator; ESS - Energy Storage System;
COORD - Coordination; COM - Communication; and ADPT - Adaptative relay settings for different microgrid operation modes.

II. VOLTAGE-BASED RELAYS

Voltage-based protection methods applied to fault detection for MGs commonly use the voltage drop in the faulted phases of the system. These protection methods are advantageous for MGs because they do not depend on the fault current amplitude. However, defining a single pickup value suitable for the different MG operation modes and DERs connections is challenging. Furthermore, because islanded MGs are weaker than grid-connected MGs, the voltage variations caused by faults are more severe, favoring the application of voltage-based relays. On the other hand, traditional overcurrent protection is more likely to fail for faults in islanded MGs.

Voltage-based protection has the challenge of maintaining protection selectivity and security since the nodal voltages due to faults can be very similar. MGs are delimited in smaller areas than distribution systems, and the electrical distance between the system nodes also decreases, leading to similar fault voltages of the backup and primary protection relays. Besides, two voltage relays installed in lateral branches may read the voltage of the same node, leading to sympathetic trip of healthy branches. Then one relay may operate for an external fault, compromising the selectivity and security of the protection.

To solve the previous issues, the authors in [14] presented a combination between the time-overcurrent relay curves and undervoltage protection philosophies to unite their advantages. So, the authors proposed the relay operation curves described by (1) and (2), where D indicates the minimum protection trip time, considered 30 ms in this paper; Vsc is the voltage measured by the relay during the short circuit; A, p, and m are the curve parameters, and TDS is the time dial setting.

$$t = \mathrm{TDS}\left(\frac{A}{\left(\frac{1}{K}\right)^{p} - 1}\right)\log_2\left(\frac{1}{K}\right)\cdot\left(\frac{1}{K}\right) + D \qquad (1)$$

$$K = \left(\frac{V_{sc}}{2}\cdot\left(1 - \frac{V_{sc}}{2}\right)\right)^{m} \qquad (2)$$

Equation (1) results in a trip time for any voltage value, even if the Vsc = 1. So, the authors proposed the relay starter criteria to prevent the relay trip during a regular MG operation. Then, the authors defined voltage and current thresholds values and established two criteria for fault detection: voltage lower than the voltage threshold Vsc<Vthr or current higher than the current threshold Isc >Ithr. Furthermore, the proposed voltage-based relays are directional. If at least one criterion from the relay starter and the directionality are satisfied, the relay operates with the time resulting from Equation (1).

However, the relay starter proposed in [14] does not mitigate the main challenges of voltage-based protection, such as security. Also, the protection settings of the method are a complex task depending on the size of the MG and the position of the relays because reverse power flow relays in lateral branches require that inverter-based generators be considered installed individually at the laterals to be set. So, if the number of terminal branches with reverse relays increases, the simulations to obtain these relays settings will increase too.

A. *Enhanced Method*

To improve the security of the strategy described in [14], the relay starter was modified to require both voltage and current to surpass their thresholds simultaneously, which means the relay will trip if both requirements are accomplished. The flowchart shown in Fig. 1 indicates the relay starter of the enhanced method. Note that if branches' relays are connected to the same bus, the voltage in both relays will be the same. However, the current of healthy branches will not exceed the current threshold, preventing sympathetic trips.

To avoid the loss of protection reliability, adaptive voltage and current thresholds were defined depending on the MG operating mode. For grid-connected scenarios, the fault current thresholds were determined, such as the inverse time overcurrent protection, as $1.5I_n$, which I_n represents the of load current considering the base scenario (grid-connected system without DERs). For the islanded MG, the fault currents are lower. So, the threshold was defined as the base scenario load current to maintain protection security. The voltage threshold for grid-connected scenarios is defined to guarantee protection security, and it was set in 1 p.u. In the islanded MG, the voltage threshold is responsible for the protection dependability with values defined as [14] in 0.85 p.u. It is important to highlight that the security parameters are sensitive to not spoil protection dependability, avoiding the protection trip for events of undervoltage or overcurrent alone.

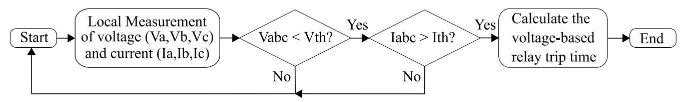

Fig. 1. Relay starter flowchart.

Besides, the proposed voltage-based relay settings method simplified the relay settings definition of [14] to reduce the number of required scenarios. Thus, the following steps describe the proposed relays settings method:

- Define the parameters m and TDS for the direct power flow relay for three-phase faults at the end of each feeder in the grid-connected system without DG. The primary protection relays settings are adjusted. Later, the TDS and m parameters of the backup relays are defined to maintain the coordination. This paper adopted the Coordination Time Interval (CTI) between primary and backup protection as 200 ms,
- Readjustment of backup protection direct relays parameter m considering the islanded MG with all the predefined DERs. In this scenario, the value of m defined must be less than the value for the grid-connected cases,
- Define the reverse relays settings for three-phase faults at the PCC in the islanded scenario considering all the DERs in operation.

The proposed relay settings definition needs only two operation scenarios to set all relays regardless of the number of lateral branches in the distribution systems. So, for a system with three lateral branch relays, the number of scenarios would be reduced by half compared to the relay settings method proposed in [14].

III. Description of the Microgrid

The electrical system analyzed was a modified 14-bus CIGRE European Configuration system for a frequency of 60 Hz. The system is described in [22] and has constant impedance loads as residential and industrial consumers. Fig. 2 shows a single-line diagram of the test system with all the DERs and voltage-based relays.

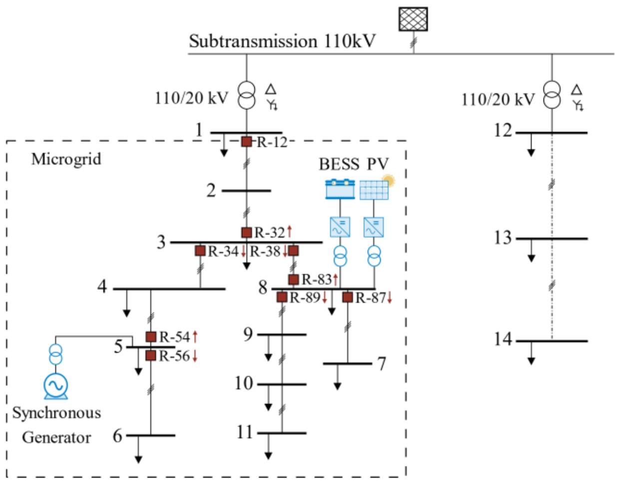

Fig. 2. Microgrid single-line diagram.

The synchronous generator has a capacity of 5 MVA with 6.6 kV and a frequency of 60 Hz, based on [23]. The synchronous generator controls the active and reactive power in the grid-connected scenarios and the voltage and frequency during islanded system operation. The transition from PQ-control to Vf-control has a delay of 100 ms, which may change depending on the islanding detection strategy used. The details of the islanded detection method are out of the scope of this paper.

This study considered the average model of the inverter of the photovoltaic system, with power of 1 MVA and configured to control active and reactive power (PQ-control) with unitary power factor in all scenarios. The modeled average model of the battery storage system has a capacity of 1 MVA, maintaining PQ-control in grid-connected systems and Vf-control for islanded operation without the synchronous generator. The analyzed scenarios described in Table II represent each study case's system loads, power, and connection of energy resources. It is noteworthy that scenario 5 (based only on inverters-based generators) could only be considered with the storage system modelling to maintain the grid voltage and frequency reference because the photovoltaic panels commonly operate with PQ-control.

The fault cases considered are described in Table III, where each row represents the number of scenarios for fault type, the resistance of fault, fault incidence angle, location of the fault, MG scenarios described in Table II, and protection method analyzed. Thus, the combination of each row represents the total number of simulations, with 3000 cases for each protection method analyzed. This study focused on the critical analysis of voltage-based protection methods. So, it was considered that the directional relay function correctly identified the current direction in all investigated cases. The test system with all DERs and respective controls was modelled in the PSCAD/EMTDC software, in which it was also performed the short circuit simulations.

TABLE II
MICROGRID SCENARIOS

Scenario	Loads	MG	DER	Active Power	Reactive Power
1	24.16 MW 6.07 Mvar	GC	-	-	-
2	24.16 MW 6.07 Mvar	GC	SG	4.88 MW	0.52 MVAr
3	24.16 MW 6.07 Mvar	GC	SG	4.89 MW	0.53 MVAr
			PV	1 MW	-
			BESS	1 MW	-
4	4.32 MW 1.43 Mvar	IL	SG*	4.11 MW	1.24 MVAr
5	1.73 MW 0.57 Mvar	IL	PV	1 MW	-
			BESS*	0.79 MW	0.33 MVAr
6	4.32 MW 1.43 Mvar	IL	SG*	2.17 MW	1.13 MVAr
			PV	1 MW	-
			BESS	1 MW	-

Microgrid (MG): GC = Grid-connected; and IL = Islanded.
Distributed Energy Resources (DER): SG = Synchronous Generator;
PV = Photovoltaic System; BESS = Battery Energy Storage System; and
* indicates the DER with Vf-control.

TABLE III
FAULT CASES ANALYZED

Variables	Description	Cases
Fault type	LG, LLG, LL, LLL/LLLG	5
Fault Resistance (Ω)	0, 10, 20, 30 and 40	5
Fault Incidence Angle	0° and 90°	2
Fault bus	B2, B3, B4, B5, B6, B7, B8, B9, B10 and B11	10
Scenarios	1, 2, 3, 4, 5 and 6	6
Protection Method	Overcurrent, JVP Method and Enhanced Method	3

IV. RESULTS AND DISCUSSION

This section shows the performance of the voltage-based relay with proposed modifications (Enhanced Method), the method described in [14], called the JVP method (Jamali Voltage-based Protection method) and the conventional overcurrent protection.

A. *Conventional Overcurrent Protection*

The overcurrent relays operate with the instantaneous and time-overcurrent settings. These relays do not have directionality. So, the backup relay (R-34 and R-38) protection zones change with the operation scenario due to the different connections of DERs. Thus, Fig. 3 represents the colormap of the relay success rate for fault resistances considering all analysis scenarios. The colormap lines represent the overcurrent relays, and the columns represent the fault resistance. The colors show the success rate of the overcurrent relay, and red indicates the lowest percentage.

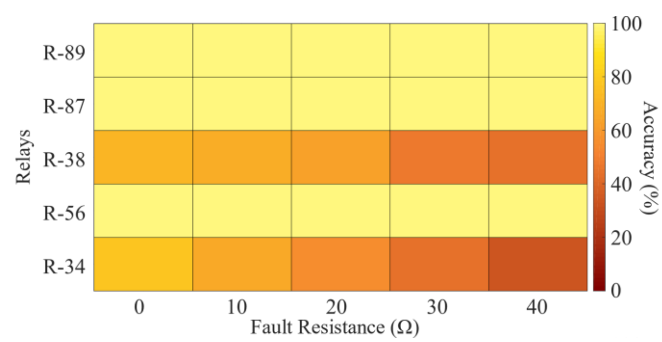

Fig. 3. Success rate of conventional overcurrent protection.

Note that low accuracy levels are associated with higher values of fault resistance, which characterize a reduction in fault current. Besides, the scenario changes affected only the performance of the backup protection relays. The primary protection relays present a success rate of almost 100% in all fault scenarios. However, the fault current reduction could slower the relay trip time. So, Fig. 4 represents a boxplot of the primary relay trip times, in which the median value is higher than 300 ms when the desired value is less than 100 ms.

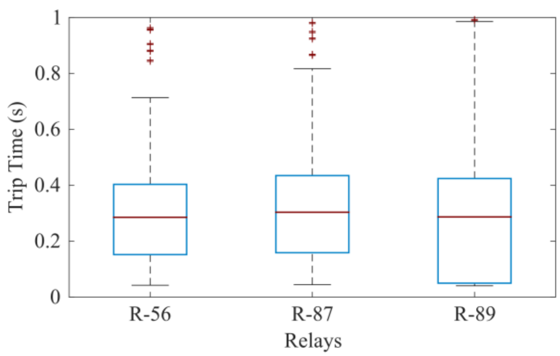

Fig. 4. Primary relays trip times for overcurrent protection.

B. *JVP Method*

The JVP method was tested for the same six scenarios, and the success rates were separated by fault resistance, as presented in Fig. 5. Note that for R-32, R-56, R-87, and R-89 relays, not even the faults with Rf = 0 obtained a success rate close to 100%. These relays operated for the change in the GS control from PQ-control to Vf-control during the transition from grid-connected to the islanded operation of the MG. This event generated a temporary voltage reduction in scenarios 4 and 6. Despite the reliability of the directional method, the primary protection relays R-56, R-87 and R-89 will always have direct power flow. So, they can operate for faults outside their protection zones (sympathetic trips) since the undervoltage criterion is enough for the relay to trip. In the scenarios only with inverter-based generators, all the relay locations experienced very low voltages. To exemplify this situation, Fig. 6 indicates the RMS fault voltages of the relays on each bus of Scenario 5 for an LG fault. Observe that the voltages measured by the relays during the fault are very low for both conditions of fault resistances, which can spoil the selectivity and security of voltage-based protection if it is not set properly.

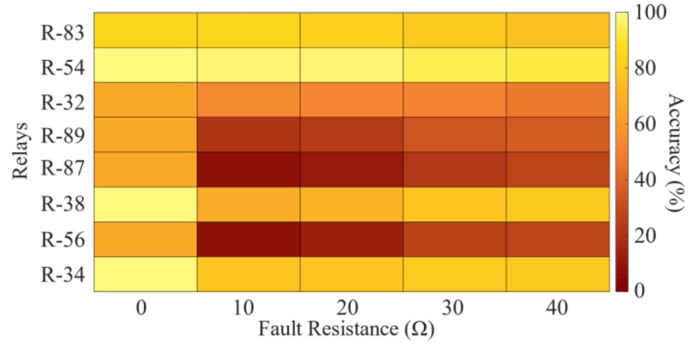

Fig. 5. Success rate of JVP Method.

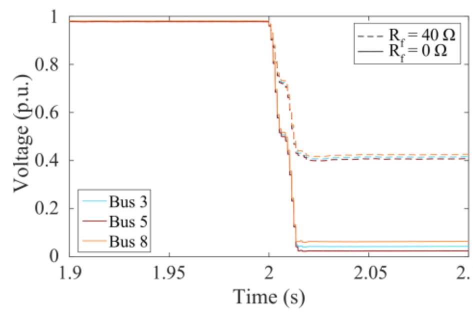

Fig. 6. Voltage behavior in Scenario 5 for an LG fault on bus 6.

C. *Enhanced Method*

The Enhanced Method obtained higher success rates than the previous methods, as presented in Fig. 7. Note that the highest fault resistances slightly reduced the relay accuracy. Besides, the Enhanced Method reduced the incorrect operation (the sympathetic trips) compared to the JVP Method. Fig. 8 shows the current and voltage on relays R-89 and R-87 for an LG fault with Rf = 20 Ω on bus 11 for Scenario 5. In the islanded scenarios, the current thresholds of the Enhanced and JVP Methods are In and 1.5 In, respectively, which are both exceeded by the fault current. The fault voltage on bus 8 (for both R-87 and R-89 relays) is lower than the threshold of both methods, which are set at 0.85 p.u. So, the JVP relays R-87 and R-89 trips for the fault on bus 11, while the Enhanced Method prevents the sympathetic trip. This improvement was obtained because the relay starter of the Enhanced Method depends on the fault current, which is not exceeded by the current of relay R-87. In addition, this strategy does not compromise the protection trip time like the conventional overcurrent method since the primary relays had average trip times close to 150 ms for grid-connected and islanded scenarios.

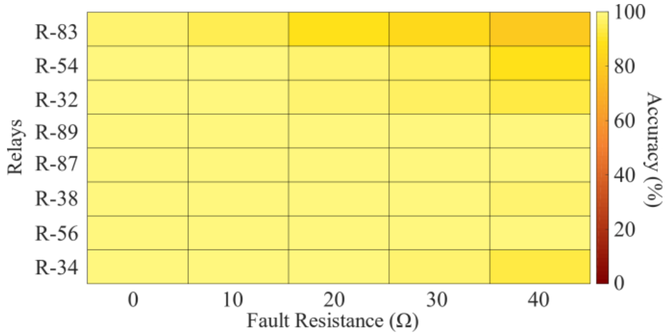

Fig. 7. Success rate of Enhanced Method.

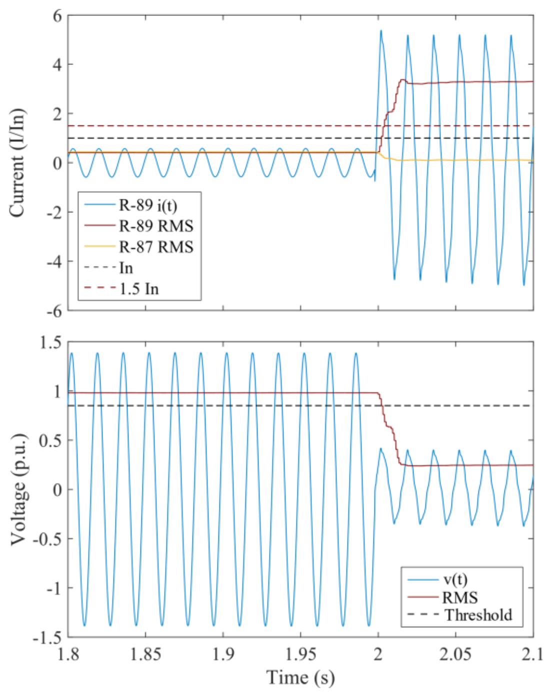

Fig. 8. Voltage and current oscillography for an LG fault with $R_f = 20\,\Omega$ on bus 11 – Scenario 5.

D. Comparative Study

Fig. 9 shows an overall assessment of the three methods for the six analyzed scenarios, where Correct Operation indicates the reliability of the technique (dependability+security), Operation Failure indicate the non-operation of the protection for fault scenarios within the relays protection zones, False trip represents the protection operation for events that are not classified as faults, and Incorrect trip indicates the protection operation for faults outside the relay protection zone (sympathetic trips). Note that the JVP Method could trip in most fault conditions analyzed (higher dependability). However, the protection security (incorrect trips and false trips) compromised the performance of the JVP method, which was lower than the conventional overcurrent protection method. The main drawback of the overcurrent method is the lack of dependability due to the lower fault currents, mainly in the islanded scenarios.

On the other hand, the Enhanced Method operated correctly for most of the analyzed cases and mitigated the security issues observed in the JVP method. Besides, the Enhanced Method had the best reliability and success rate among the three protection methods investigated in this paper. This comprehensive analysis of the protection reliability shows that the methods with the highest dependability are not always the most efficient, especially for MGs protection. Since the MGs may present oscillations due to changes in the operating mode or the disconnection of DERs that can generate false trips or sympathetic trips of the relays, compromising the protection security and the MG operation.

Fig. 10 indicates the CTI of the relay pairs of the three methods considering all analyzed scenarios. All CTI medians are above the 200 ms line, with just some outliers violating the coordination condition. However, due to the fault current path changes, the overcurrent backup relays tripped for less than half of the cases for grid-connected scenarios, reducing even more for the islanded system. The JVP and Enhanced Methods were not affected by the islanded operation and presented similar coordination performances, which was expected because they were adjusted with the same parameters m and TDS. However, the relay starter differs, changing the cases in which the backup protection trips, and the CTI could be analyzed.

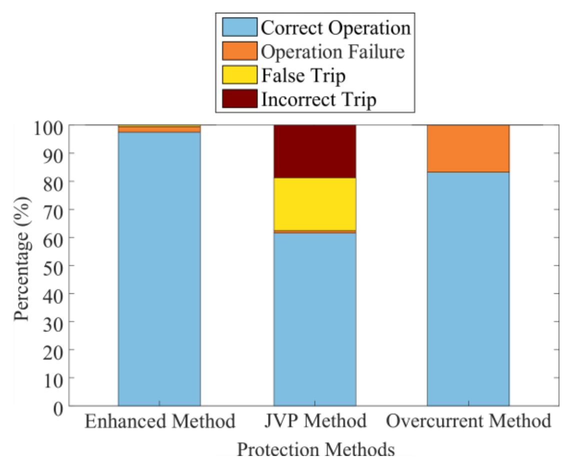

Fig. 9. Overall performance of the analyzed methods.

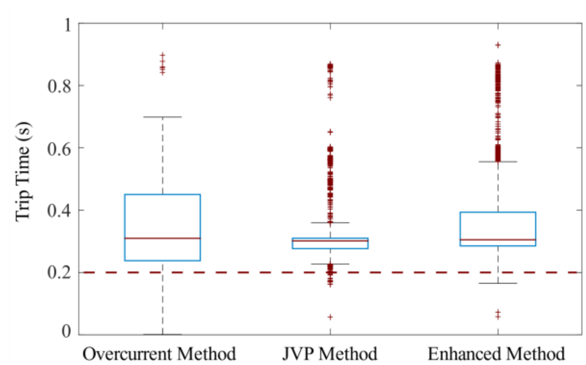

Fig. 10. Coordination time interval.

V. CONCLUSIONS

The analysis of faults in MGs shows that high fault currents and lower voltage drops characterize grid-connected scenarios. However, faults in the islanded system have expressive voltage drops and lower fault currents, impacting current-only protection methods. The voltage mapping indicates a slight variation of voltages in the system buses during the fault, which can spoil the selectivity and security of methods based only on voltage. The comparative study showed the superiority of the enhanced approach against the other two analyzed methods since the conventional overcurrent is limited to fault currents amplitudes, and the JVP Method did not achieve protection security for several operating scenarios not analyzed in [14]. Thus, the enhanced method guaranteed the same coordination performance as the JVP method, with higher immunity against false and incorrect trips and more reliability through several transient simulations. Future studies will evaluate the voltage-based relay performance with changes in the MG topology.

VI. REFERENCES

[1] N. Hatziargyriou, H. Asano, R. Iravani, and C. Marnay, "Microgrids," *IEEE Power and Energy Magazine*, 2007.

[2] IEEE, *IEEE 2030.7-2017 Standard for the Specification of Microgrid Controllers*, 2017.

[3] DOE, "U.S. Department of Energy. Summary report: 2012 DOE microgrid workshop," *Office of Electricity Delivery and Energy Reliability Smart Grid R&D Program*, 2012.

[4] P. H. Barra, D. V. Coury, and R. A. Fernandes, "A survey on adaptive protection of microgrids and distribution systems with distributed generators," *Renewable and Sustainable Energy Reviews*, vol. 118, no. June 2019, p. 109524, 2020.

[5] B. J. and Brearley and R. R. Prabu, "A review on issues and approaches for microgrid protection," *Renewable and Sustainable Energy Reviews*, vol. 67, pp. 988–997, 2017.

[6] A. Hirsch, Y. Parag, and J. Guerrero, "Microgrids: A review of technologies, key drivers, and outstanding issues," *Renewable and Sustainable Energy Reviews*, vol. 90, no. September 2017, pp. 402–411, 2018.

[7] A. Hooshyar and R. Iravani, "Microgrid Protection," *Proceedings of the IEEE*, vol. 105, no. 7, pp. 1332–1353, 2017.

[8] H. Al-Nasseri, M. A. Redfern, and F. Li, "A voltage based protection for micro-grids containing power electronic converters," *2006 IEEE Power Engineering Society General Meeting, PES*, pp. 1–7, 2006.

[9] E. Sortomme, S. S. Venkata, and J. Mitra, "Microgrid protection using communication-assisted digital relays," *IEEE Transactions on Power Delivery*, vol. 25, no. 4, pp. 2789–2796, 2010.

[10] X. Wang, Y. Li, and Y. Yu, "Research on the relay protection system for a small laboratory-scale microgrid system," in *2011 6th IEEE Conference on Industrial Electronics and Applications*, 2011, pp. 2712–2716.

[11] X. Wang, J. Qi, Y. Hou, Y. Wang, W. Xu, D. Wang, and Z. Jiao, "Studies on fault analysis and protection configuration schemes in an isolated micro-grid," *IEEE Power and Energy Society General Meeting*, vol. 2014-Octob, no. October, pp. 1–5, 2014.

[12] K. A. Saleh, H. H. Zeineldin, A. Al-Hinai, and E. F. El-Saadany, "Optimal Coordination of Directional Overcurrent Relays Using a New Time-Current-Voltage Characteristic," *IEEE Transactions on Power Delivery*, vol. 30, no. 2, pp. 537–544, 2015.

[13] S. Jamali and H. Borhani-Bahabadi, "Non-communication protection method for meshed and radial distribution networks with synchronous-based DG," *International Journal of Electrical Power and Energy Systems*, vol. 93, pp. 468–478, 2017.

[14] ——, "Protection Method for Radial Distribution Systems with DG Using Local Voltage Measurements," *IEEE Transactions on Power Delivery*, vol. 34, no. 2, pp. 651–660, 2019.

[15] P. Mishra, A. K. Pradhan, and P. Bajpai, "A Positive Sequence Relaying Method for Solar Photovoltaic Integrated Distribution System," *IEEE Transactions on Power Delivery*, 2020.

[16] O. Núñez-Mata, R. Palma-Behnke, F. Valencia, P. Mendoza-Araya, and G. Jiménez-Estévez, "Adaptive protection system for microgrids based on a robust optimization strategy," *Energies*, vol. 11, no. 2, 2018.

[17] T. The Hoang, Q. Tuan Tran, and Y. Besanger, "An advanced protection scheme for medium-voltage distribution networks containing low-voltage microgrids with high penetration of photovoltaic systems," *International Journal of Electrical Power and Energy Systems*, vol. 139, no. February, p. 107988, 2022.

[18] J. Ma, W. Ma, X. Wang, and Z. Wang, "Distribution Network With Distributed Generations tension pour réseaux de Distribution avec Générations Distribuées," *Canadian Journal of Electrical and Computer Engineering*, vol. 36, no. 4, pp. 142–151, 2013.

[19] S. Ranjbar, A. R. Farsa, and S. Jamali, "Voltage-based protection of microgrids using decision tree algorithms," *International Transactions on Electrical Energy Systems*, vol. 30, 2020.

[20] R. Mohanty, P. Chen, and L. A. Tuan, "Current restrained undervoltage protection scheme of converter dominated microgrids," *IET Conference Publications*, vol. 2020, no. CP771, pp. 1–6, 2020.

[21] H. Ebrahimi, A. Yazdaninejadi, S. Golshannavaz, and S. Teimourzadeh, "An ENS-Oriented Voltage Protection Scheme for Inverter-based Generators in Active Distribution Networks," *IEEE Transactions on Smart Grid*, vol. 13, no. 4, pp. 2639–2649, 2022.

[22] CIGRE, "Benchmark Systems for Network Integration of Renewable Energy Resources," 2014.

[23] F. A. Moura, J. R. Camacho, M. L. Chaves, and G. C. Guimarães, "Independent power producer parallel operation modeling in transient network simulations for interconnected distributed generation studies," *Electric Power Systems Research*, vol. 80, no. 2, pp. 161–167, 2010.