Periodica Polytechnica Electrical Engineering and Computer Science, 68(1), pp. 27–36, 2024

Investigating the Performance of Non-standard Overcurrent Relay with Integration of Photovoltaic Distributed Generation in Power Distribution System

Mohamed Zellagui[1*], Nasreddine Belbachir[2], Mohammed Amroune[3], Claude Ziad El-Bayeh[4]

[1] Department of Electrical Engineering, University of Batna 2, Route de Constantine 53., 05078 Batna, Algeria
[2] Department of Electrical Engineering, University of Mostaganem, National Road 11., 27000 Mostaganem, Algeria
[3] Department of Electrical Engineering, University of Setif 1, Route de Béjaia, 19000 Setif, Algeria
[4] Canada Excellence Research Chairs Team, Concordia University, Guy St. 1250., QC H3G 1M8 Montreal, Canada
[*] Corresponding author, e-mail: m.zellagui@univ-batna2.dz

Received: 01 January 2023, Accepted: 07 June 2023, Published online: 25 August 2023

Abstract

The electricity demand is increasing daily, so the generation power should be raised to fulfil that demand. Renewable distributed generation-based photovoltaic sources are one of the best solutions to satisfy the Power Distribution System (PDS) as long as the fossil resources are on the verge of extinction. At the same time, connecting the Photovoltaic Distributed Generation (PVDG) to the PDS may cause issues with the system's technical parameters, such as a protection system based on overcurrent relays, unless they are optimally allocated. In this context, this paper will be devoted to optimally allocating multiple PVDG units in the PDS using the Slime Mould Algorithm (SMA), meanwhile studying the impact of that optimal integration on the overcurrent protection system that will be represented and based on various chosen non-standard overcurrent relays (NS-OCRs) which many researchers develop, and trying to figure out and pick up the best type that provides improvement to the protection system including the minor impact on the coordination time interval. To achieve the maximum and best of the requested results, a multi-objective function was proposed to be minimized based on the sum of total active power loss, total voltage deviation, and total operating time of the relays.

Keywords

optimal allocation, photovoltaic distributed generation, power distribution system, non-standard overcurrent relays, operation time, integration impact assessment

1 Introduction

The use of green energy resources has been raised in the last decade. The interest of Renewable Energy Sources (RESs) is to reveal an economic and technical improvisation of the presence of RESs in the Power Distribution System (PDS), where at the same time, minimize the requirement of the increased load demand in the future, also mitigate the polluted emission [1].

Recently, PV technologies have been implemented rapidly, which makes that technology viable even for power generation in PDS. The considerable role of PV integration in the PDSs as a major part of RES is being extensively used on a full scale. Despite its promising success, PV integration reveals different problems, and its effect on the PDS should address for seamless presence in the PDS [2, 3].

Nevertheless, as the capacity of PV rises and starts to represent a significant portion of produced power, concerns about grid quality and reversed power flow, also the possibility of a miscoordination in the protection equipment of the distribution grid [4, 5].

Despite the actual merits that the installation of Photovoltaic Distributed Generation (PVDG) units provides to the distribution system, their apparent effect on the protection system reveals many concerns and challenges regarding how a fault current would be sensed and removed in PDSs [6]. The installation of PVDGs into distribution systems can present either positive or negative effects depending on the characteristics of the PDS and the PVDG itself [7].

All trendy research shows that this type of conventional protection is threatened by installing PVDG in the

Cite this article as: Zellagui, M., Belbachir, N., Amroune, M., El-Bayeh, C. Z. "Investigating the Performance of Non-standard Overcurrent Relay with Integration of Photovoltaic Distributed Generation in Power Distribution System", Periodica Polytechnica Electrical Engineering and Computer Science, 68(1), pp. 27–36, 2024. https://doi.org/10.3311/PPee.21780

PSD [8]. Besides, in recent literature, many researchers studied and analyzed the effect of DG installation in distribution system on system of protection as:

- impact on OCR relay coordination for different scenarios [9],
- fault current characteristics for the OCR performance under variant fault scenarios [10],
- impact on short-circuit current and fault detection in PDS in the presence of DG sources [11],
- analyzed time inverse characteristics of standard relays [12],
- investigation of RES impacts on standard protection relay operate under different conditions [13],
- impact on transient stability constrained by conventional overcurrent relay [14],
- impact on variable tripping time differential protection operation [15],
- impact on differential relay coordination considering various topology [16],
- impact on protection of autonomous micro grids [17],
- lightning protection performance with PV integration in distribution system [18],
- impact on current differential protection system [19],
- impact on differential sequence component protection scheme [20],
- impact on the reliability of transformer differential protection [21],
- impact on existing protective schemes and investigate reverse power relay [22],
- studies the impact on overvoltage relay based Thevenin equivalent impedance [23].

Recently, the Salp Swarm Algorithm (SSA) was introduced as a modern algorithm that was introduced by Dr. Mirjalili in 2017 [24] and applied to various problems in power system engineering [25]. By following the context, this paper is consisted of finding the optimal allocation of multiple PVDG units into different distribution systems of the Institute of Electrical and Electronics Engineers (IEEE): IEEE 12-bus in [26], IEEE 33-bus in [27] and IEEE 69-bus in [28] test distribution systems.

The proposed multi-objective function (MOF) in this paper minimizes the Total Voltage Deviation (TVD), the Total Active Power Loss (TAPL), and the Total Operation Time (TOT), all simultaneously using the Slime Mould Algorithm (SMA) approach while investigating the impact of that optimal integration on various recent types of non-standard overcurrent relays (NS-OCRs).

It is chosen five types of NS-OCRs for this study, wherein generally it will be five studied cases to achieve a better contribution about the type that should be widely used, besides guaranteeing an optimal function of the protection system with and without the PVDG inclusion while avoiding the miscoordination for three test systems.

2 Mathematical problem formulation

2.1 Multi-objective function

The proposed MOF in this paper was devoted to solving the allocation problem of multiple PVDG units into different PDS while minimizing the three technical parameters simultaneously, while it would be formulated as:

$$\mathrm{MOF} = \mathrm{Minimize} \sum_{i=1}^{N_{bus}} \sum_{j=2}^{N_{bus}} \sum_{i=1}^{N_R} \left[\mathrm{TAPL}_{i,j} + \mathrm{TVD}_j + \mathrm{TOT}_i \right]. \quad (1)$$

The TAPL in the distribution line is presented as [29, 30]:

$$\mathrm{TAPL}_{i,j} = \sum_{i=1}^{N_{bus}} \sum_{j=2}^{N_{bus}} \mathrm{APL}_{i,j}, \quad (2)$$

$$\mathrm{APL}_{i,j} = \alpha_{ij} \left(P_i P_j + Q_i Q_j \right) + \beta_{ij} \left(Q_i P_j + P_i Q_j \right), \quad (3)$$

$$\alpha_{ij} = \frac{R_{ij}}{V_i V_j} \cos\left(\delta_i - \delta_j\right), \ \beta_{ij} = \frac{R_{ij}}{V_i V_j} \sin\left(\delta_i - \delta_j\right). \quad (4)$$

The second parameter is TVD [30, 31]:

$$\mathrm{TVD}_j = \sum_{j=2}^{N_{bus}} \left| 1 - V_j \right| . \quad (5)$$

The TOT of NS-OCRs is presented as [30–33]:

$$\mathrm{TOT}_i = \sum_{i=1}^{N_R} T_i , \quad (6)$$

$$I_F = \frac{V_F}{Z_{ij}}. \quad (7)$$

The relay operation time (T) formulation is varied based on the chosen relay's type, as mentioned in Table 1 [34–38]. Before, the NS-OCRs detected and removed faults based only on the fault current value.

However, recently, the NS-OCRs became widely accessible by measuring both parameters of the line current and voltage values via current and voltage transformers to diagnose the faulty parts of the power systems and also to guarantee the reliable performance of the protection system, especially while the DG units are being integrated. Many researchers developed various NS-OCRs based either on the double function of detecting fault current and

Table 1 The operation time of various types of NS-OCR

NS-OCRs types	Ref.	Mathematical equations of operation time
NS-OCRs 1	[34]	$T=\left(\frac{1}{e^{(1-V_F)}}\right)^k\times\left(\frac{A}{\left(I_F/I_P\right)^B-1}\right)\times\text{TDS}$
NS-OCRs 2	[35]	$T=\left(\frac{V_F}{e^{(k\times V_F)}}\right)\times\left(\frac{A}{\left(I_F/I_P\right)^B-1}\right)\times\text{TDS}$
NS-OCRs 3	[36]	$T=\left(\frac{1}{e^{(1-V_F)}}\right)^k\times\left(\frac{A}{\left(I_F/I_P\right)^B-1}+C\right)\times\text{TDS}$
NS-OCRs 4	[37]	$T=\left(\frac{A}{\left(I_F/I_P\right)^B-1}+\chi\right)\times\text{TDS}+\xi$
NS-OCRs 5	[38]	$T=\left(\frac{A}{\left(k\times I_F/I_P\right)^B-1}\right)\times\text{TDS}$

voltage or by including some constants in the mathematical formulation of the operation time of NS-OCRs. Table 1 contains the chosen NS-OCRs of this study.

2.2 Equality constraints

The equality constraints of the distribution system are represented by the next equations:

$$P_G+P_{\text{PVDG}}=P_D+P_{Loss}\,, \tag{8}$$

$$Q_G=Q_D+Q_{Loss}\,. \tag{9}$$

2.3 Distribution line constraints

The distribution line constraints are represented by:

$$V_{\min}\le\left|V_i\right|\le V_{\max}\,, \tag{10}$$

$$\left|1-V_j\right|\le\Delta V_{\max}\,, \tag{11}$$

$$\left|S_{ij}\right|\le S_{\max}\,. \tag{12}$$

2.4 The PVDG units' constraints

The PVDG units' inequality constraints are expressed as:

$$P_{\text{PVDG}}^{\min}\le P_{\text{PVDG}}\le P_{\text{PVDG}}^{\max}\,, \tag{13}$$

$$\sum_{i=1}^{N_{\text{PVDG}}}\text{PVDG}\left(i\right)\le\sum_{i=1}^{N_{bus}}P_D\left(i\right), \tag{14}$$

$$2\le\text{PVDG}_{Position}\le N_{bus}\,, \tag{15}$$

$$N_{\text{PVDG}}\le N_{\text{PVDG}\times\max}\,, \tag{16}$$

$$n_{\text{PVDG},i}\,/\,Location\le 1\,. \tag{17}$$

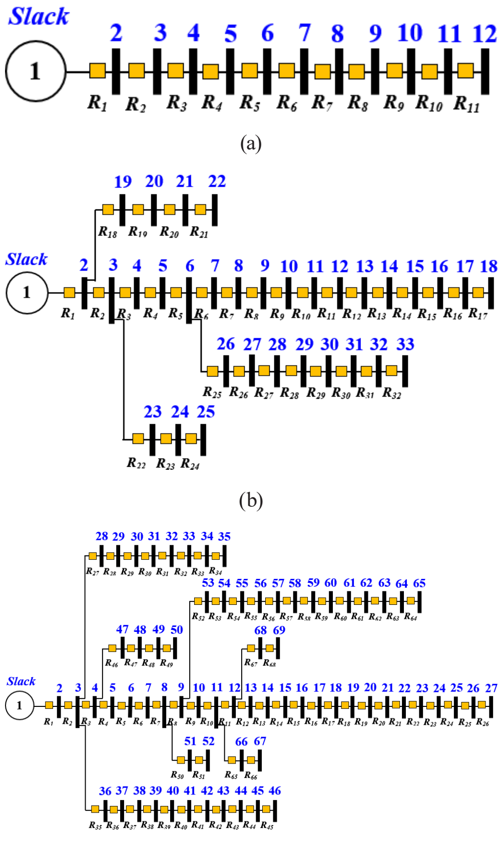
3 Analyzing and discussions of optimal results

The Slime Mould Algorithm (SMA) was tested and proved on the standards IEEE 12-bus [26], 33-bus [27], and 69-bus [28], as represented in Fig. 1. The base voltage equals 11 kV for the IEEE 12-bus and 12.66 kV for the 33- and 69-bus standards.

The total demand of loads is 435.00 kW and 405.00 kVar for the first PDS, 3715.00 kW and 2300.00 kVar for the second PDS, and 3790.00 kW and 2690.00 kVar for the third PDS. Each system's bus is protected by an OCR considered primary, followed, and covered by its backup. Between the mentioned relays, a coordination time interval is set above 0.2 seconds. The MATLAB software, version (R2022b) [39] on a computer equipped with an Intel(R) Core i7-1065G7 CPU running at 1.50 GHz and 16 GB RAM is used to implement the SMA approach for three IEEE standard test systems [26–28].

Fig. 2 illustrates the convergence curves while minimising the MOF, including all types of NS-OCRs.

By analyzing the convergence curves shown in Fig. 2, it is clear that the SMA approach was capable of delivering very favorable results by optimally allocating the

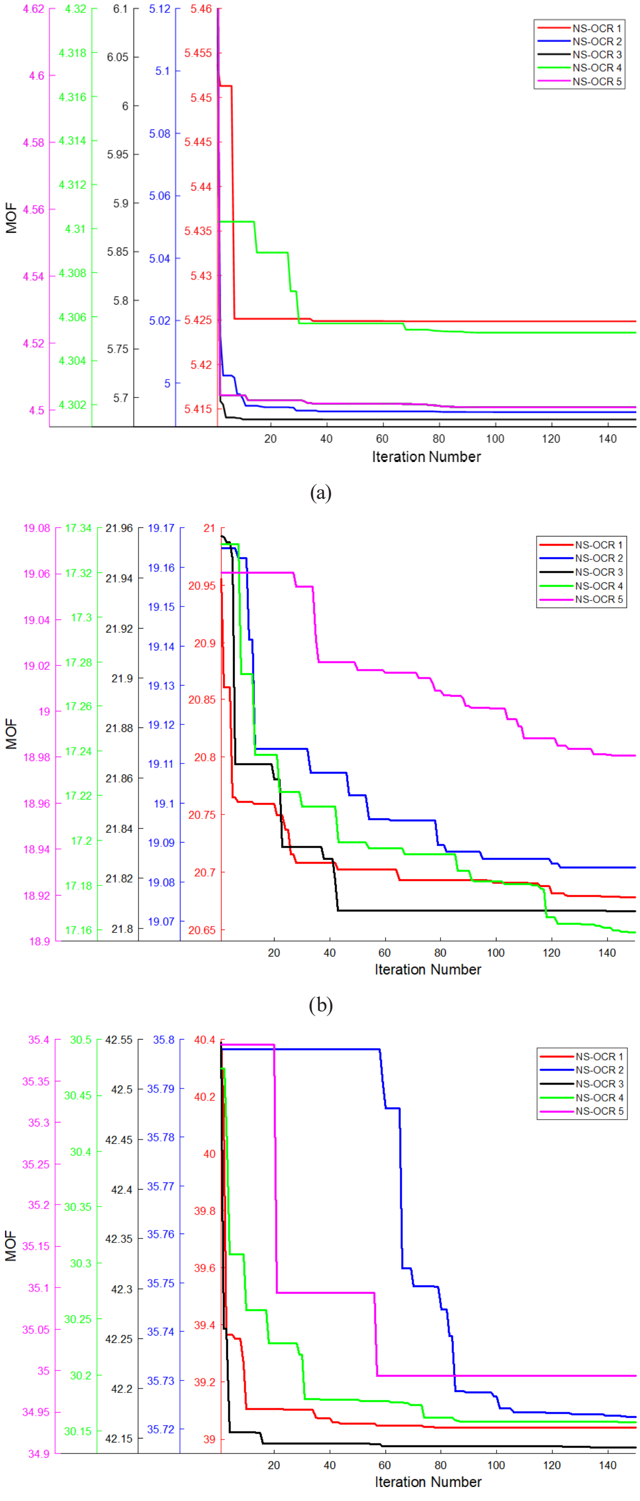


(a)

(b)

(c)

Fig. 1 Single diagram of power distribution systems; (a) IEEE 12-bus; (b) IEEE 33-bus; (c) IEEE 69-bus



(a)

(b)

(c)

Fig. 2 Convergence curves for various NS-OCRs applied; (a) IEEE 12-bus; (b) IEEE 33-bus; (c) IEEE 69-bus

PVDG units into the three studied PDS while minimizing the multi-objective function every time the NS-OCRs type was changed.

By comparing the minimum values of MOF, it is evident that the case when the NS-OCRs 4 was present is the one that provided the best MOF minimization results and values until 4.30 for the standard IEEE 12-bus [26], until 17.15 for the standard IEEE 33-bus [27], and until 30.15 for the standard IEEE 69-bus [28], including a late convergence characteristic which seems mostly settles down after 80 iterations for the IEEE 12-bus and 69-bus PDS, meanwhile after 140 iterations for the IEEE 33-bus PDS.

Tables 2 to 4 represents the results after optimization of multiple PVDG units' allocation in the presence of the various types of NS-OCRs using the SMA approach.

The optimized results mentioned in Tables 2 to 4 reveal that the optimal integration of the multiple PVDG units into all the studied test systems PDS based on using the Slime Mould Algorithm had a considerable impact on all levels of study, even for all the cases of the NS-OCRs type.

By comparing the studied cases when the NS-OCRs was present, it is clear that the optimal and best results were achieved for the case of NS-OCRs 4, which delivered the minimum values of MOF until 4.30 for the standard IEEE 12-bus [26], until 17.15 for the standard IEEE 33-bus [27], and until 30.15 for the standard IEEE 69-bus [28].

Including the minimum values of each of the parameters of TOT and TVD on their own, where until 4.00 seconds and 0.28 p.u., 16.15 seconds and 0.89 p.u. also 29.00 seconds and 1.02 p.u. for the first, second and third test systems PDS respectively, except for the term of TAPL which the case of the NS-OCRs 5 presence provided the best results of minimization for the three studied systems PDS until 11.20 kW, 84.49 kW, and 70.05 kW, respectively.

Fig. 3 represents the voltage profiles of various NS-OCRs types after integrating PVDG units in all test systems.

From the results in Fig. 3, it is clear that the optimal integration of multiple PVDG units into the three test systems has a considerable impact by ameliorating the voltage profiles in each of their buses, even while varying and changing the chosen relays NS-OCRs.

Another remark is that the presence of the type NS-OCRs 4 was the superior and best case where the voltage profiles got improved, which is clearly based on the minimized value of voltage deviation as mentioned previously, where its value has been reduced from a total value of 0.44 p.u. until 0.28 p.u. for the standard IEEE 12-bus [26], from 1.81 p.u. until 0.89 p.u. for the standard IEEE 33-bus [27], and from 1.87 p.u. until 1.02 p.u for the standard IEEE 69-bus [28]. For this reason, the formulation of the voltage deviation is

Table 2 Optimization results for types of NS-OCRs using SMA approach for IEEE 12-bus

NS-OCRs types		PVDG parameters		TAPL (kW)	TVD (p.u)	TOT (sec)	MOF
		Bus	PPVDG (MW)				
Basic case		–	–	20.83	0.44	5.29	–
After installation, PVDG units	NS-OCRs 1	3	0.0100	12.30	0.32	5.09	5.42
		11	0.0100				
		12	0.1368				
	NS-OCRs 2	3	0.0598	11.37	0.29	4.68	4.99
		6	0.0100				
		12	0.1924				
	NS-OCRs 3	3	0.0100	12.35	0.32	5.34	5.67
		5	0.0100				
		12	0.1353				
	NS-OCRs 4	3	0.6276	13.07	0.28	4.00	4.30
		9	0.0683				
		10	0.1347				
	NS-OCRs 5	3	0.0338	11.21	0.29	4.19	4.50
		8	0.0153				
		9	0.2883				

Table 3 Optimization results for types of NS-OCRs using SMA approach for IEEE 33-bus

NS-OCRs types		PVDG parameters		TAPL (kW)	TVD (p.u)	TOT (sec)	MOF
		Bus	PPVDG (MW)				
Basic case		–	–	210.98	1.81	20.50	–
After installation, PVDG units	NS-OCRs 1	4	1.1276	95.07	1.11	19.41	20.67
		16	0.4421				
		30	0.5492				
	NS-OCRs 2	5	2.3385	101.76	0.93	18.03	19.08
		6	0.8370				
		16	0.3838				
	NS-OCRs 3	2	0.3003	110.56	0.95	20.72	21.80
		5	2.9992				
		12	0.3853				
	NS-OCRs 4	5	2.0558	111.56	0.89	16.11	17.15
		13	0.5501				
		27	1.3650				
	NS-OCRs 5	5	1.7999	84.49	0.91	16.60	18.98
		13	0.7546				
		30	0.9904				

represented as the nominal value of 1 p.u. minus the actual voltage's value at the base case, as previously noted.

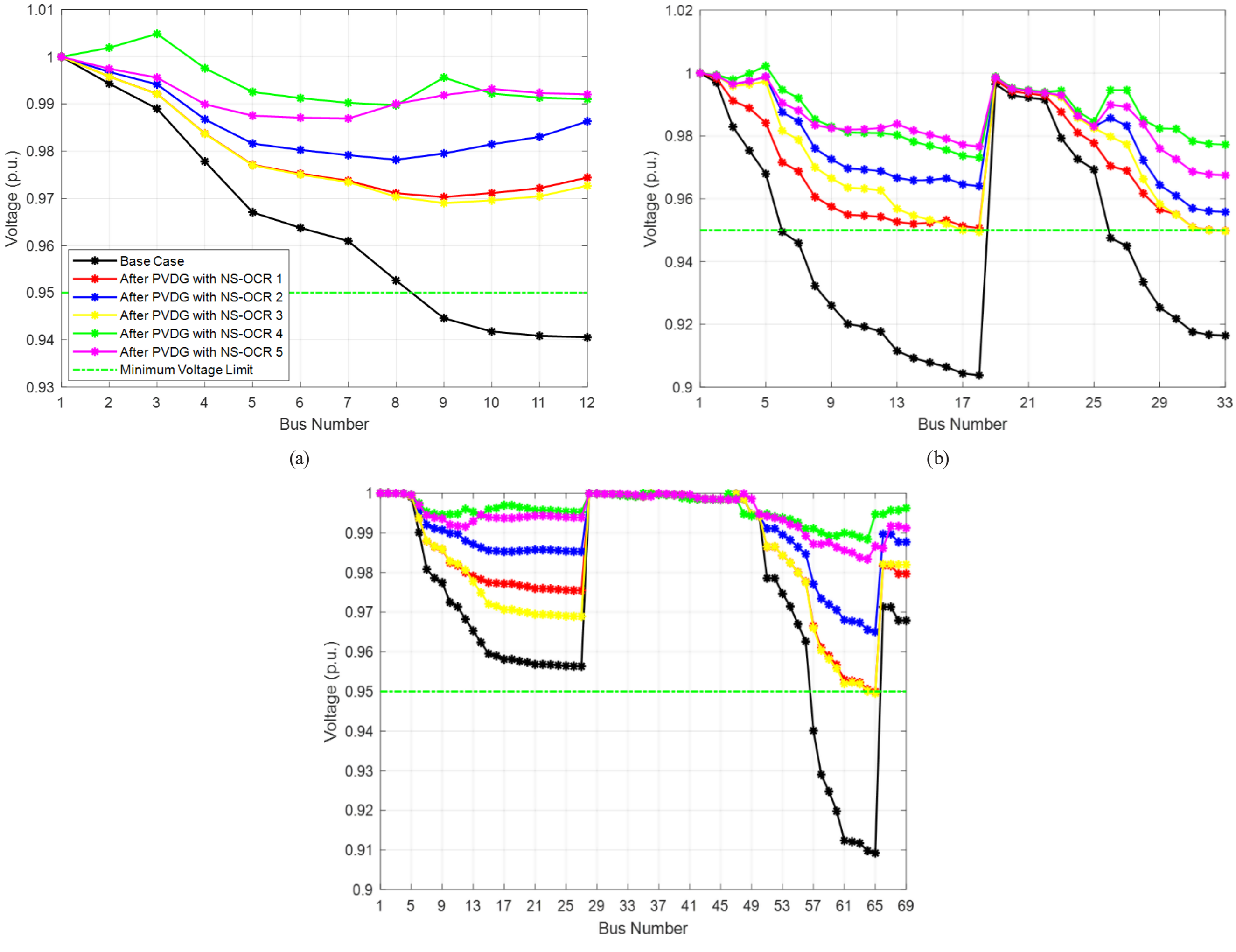
Fig. 4 shows the operating time of all types of NS-OCRs after the presence of PVDG units in all test systems.

Overcurrent relays are dispositive that widely used in power distribution systems to cover and ensure their protection against fault currents where their principal task is to sense and detect the fault current and give the order to the breaker to remove the fault by opening and to disconnect the circuit when the abnormal conditions occurred. They are represented by the formulation of their operation time, which is related to the level of fault current, time dial setting, and some other constants depending on the type of the OCR relay.

Minimizing the operation time of the relays is very beneficial and favorable in many aspects, such as protecting the parts of the targeted system, extending the equipment's lifetime, and maintaining the continuity of service.

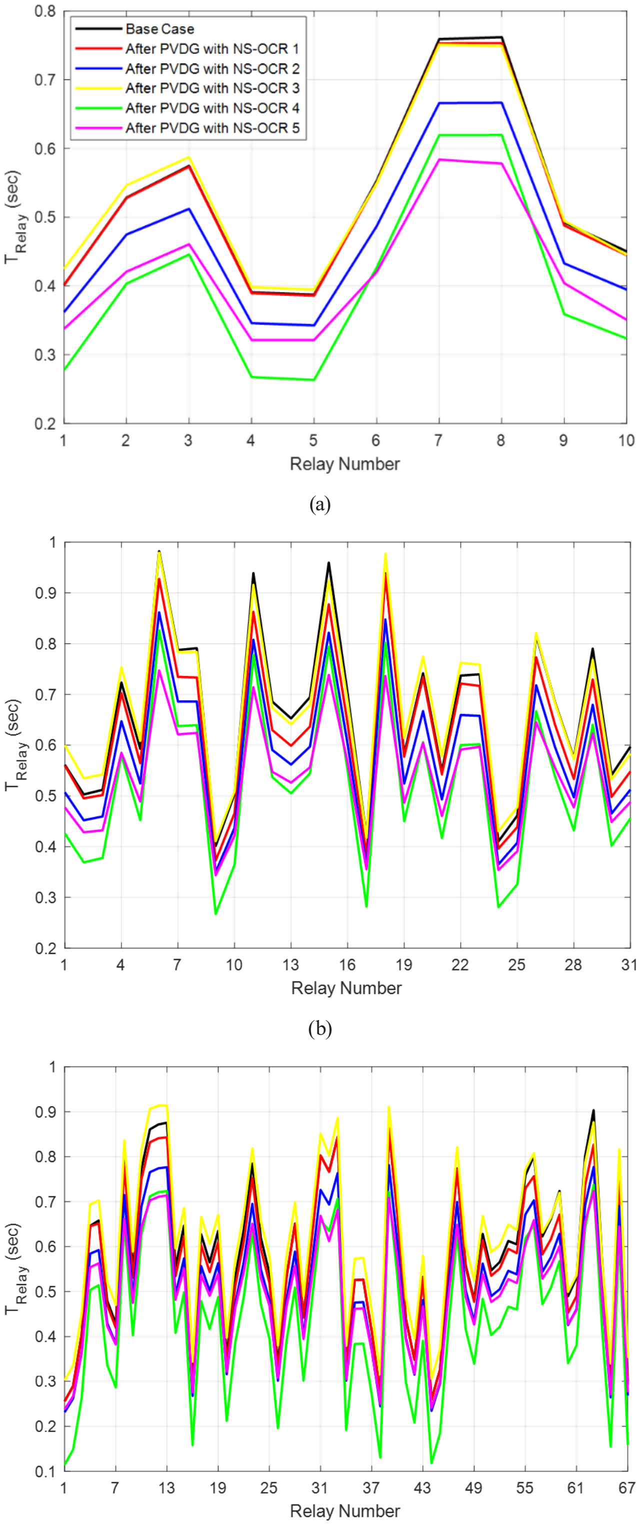
Table 4 Optimization results for types of NS-OCRs using SMA approach for IEEE 69-bus

NS-OCRs types		PVDG parameters		TAPL (kW)	TVD (p.u)	TOT (sec)	MOF
		Bus	PPVDG (MW)				
Basic case		–	–	224.94	1.87	38.70	–
After installation, PVDG units	NS-OCRs 1	3	0.4330	98.43	1.24	37.71	39.03
		18	0.3000				
		61	1.0056				
	NS-OCRs 2	11	0.4850	75.38	1.07	34.52	35.72
		22	0.3016				
		61	1.3411				
	NS-OCRs 3	3	0.3011	126.4	1.12	41.20	42.14
		62	0.9699				
		69	0.3540				
	NS-OCRs 4	3	0.3013	73.71	1.02	29.00	30.15
		17	0.6514				
		61	1.9710				
	NS-OCRs 5	12	0.6436	70.50	1.03	33.11	34.99
		22	0.3211				
		61	1.8358				



(a) (b) (c)

Fig. 3 The voltage profiles for various NS-OCRs studied; (a) IEEE 12-bus; (b) IEEE 33-bus; (c) IEEE 69-bus



(a)

(b)

(c)

Fig. 4 Operation time for various NS-OCRs studied; (a) IEEE 12-bus; (b) IEEE 33-bus; (c) IEEE 69-bus

The results shown in Fig. 4 reveal the effect of the PVDG units' optimal presence in the studied PDS on the chosen NS-OCRs, where it is clear that there was a clear and significant impact on all types studied for the three systems where the operation time was considerably minimized as long as the operation time is related to the fault current, where this last is proportional to the voltage values, where the more the voltage improved, the fault current raised and consequently, the operation time got minimized. The biggest and the best impact of that minimization was clear when using the NS-OCRs 4, which provided the minimum values in all the relays of protection for the three test systems, also clearly got reduced from a total value of 5.29 seconds until 4.19 seconds for the 12-bus, from 20.57 seconds until 16.63 seconds for the 33-bus and finally from a total value of 38.70 seconds until 33.10 seconds for the 69-bus.

Fig. 5 represents the CTI value for the studied cases of the NS-OCRs presence after the optimal installation of PVDG units in the three distribution systems.

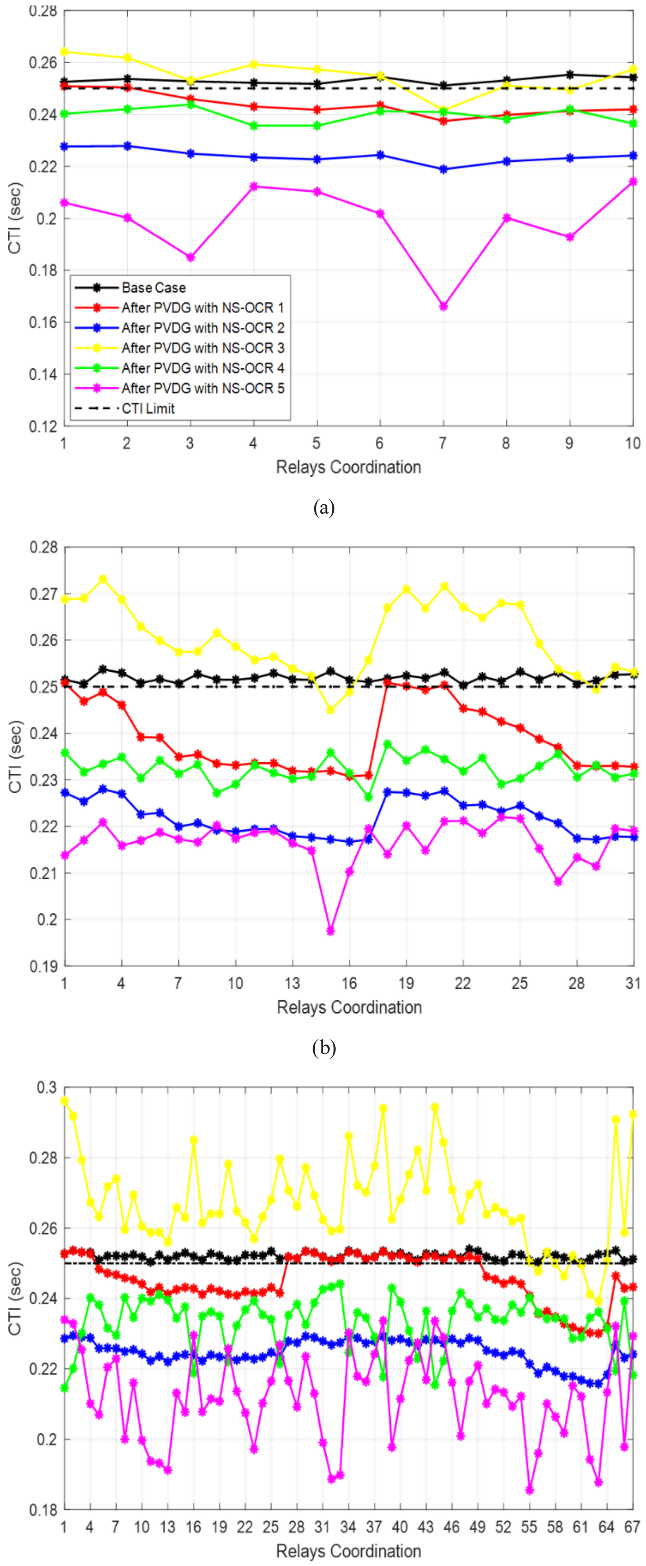
The coordination time interval is the delay between the primaries and backups relays, which is set above 0.2 seconds between all the NS-OCRs for three test systems. It is clear that after the optimal integration of the multiple PVDG units into all PSD studied, the coordination time interval was significantly minimized between all the studied NS-OCRs with different impacts in each.

The best and the closest results that did not get reduced far from the referenced values at the basic case and remained above the limit of 0.2 seconds for the three test systems are the results from the use of relays NS-OCRs 1, NS-OCRs 2, NS-OCRs 3, and NS-OCRs 4, where the worst one was the NS-OCRs 5 which got reduced under the allowable limit of 0.2 seconds and led to the risk of having a miscoordination when the fault current occurs.

In conclusion, the NS-OCRs 4 is the best choice because its presence in the three distribution systems provided the minimum values of MOF, the optimal values, and the operation time results, including maintaining the CTI interval above the allowable limit of 0.2 seconds.

4 Conclusions

This paper was devoted to solving the problem of the optimal allocation of multiple PVDG units into different power distribution systems using a recent metaheuristic optimization algorithm called the SMA algorithm, including investigating the impact of that optimal integration on various recent types of non-standard overcurrent relays that been proposed by many researchers, while developing and minimizing a multi-objective function that represented as the total of the technical parameters of TVD, TAPL, and TOT for three standards IEEE 12-, 33- and 69-bus [26–28].



(a)

(b)

(c)

Fig. 5 Coordination time interval for various NS-OCRs applied; (a) IEEE 12-bus; (b) IEEE 33-bus; (c) IEEE 69-bus

The simulation results showed that the SMA approach, in this case, offered favorable results by minimizing the active power losses, enhancing the voltage profiles, and improving the protection system simultaneously when optimally integrating the PVDG units and minimizing the multi-objective function.

These achievements have been reached while satisfying the system's operational constraints. Also, the obtained results reflect that the overcurrent relay is an essential element to cover and satisfy the protection system. As previously discussed, the chosen types of NS-OCRs used in this study revealed good behavior and provided good results with much better and superior achievement from the NS-OCRs 4.

At least, it is recommended to widely utilize the type of NS-OCRs 4 in a practical distribution system due to its benefits in showing the best behaviors and results of operation time minimization when the PVDG is connected while maintaining coordination within the allowable limits.

Nomenclature

Parameters of protection relay

T_i	Relay operation time
V_F	Measured fault voltage magnitude
I_F	Measured fault current magnitude
TDS	Time Dial Setting
I_P	Pickup current
CTI	Coordination Time Interval
A, B, k	Relays constants
C	Constant for the NS-OCRs 3
χ, ξ	Constant for the NS-OCRs 4
N_R	Number of relays

Parameters of problem formulation

TAPL	Total active power loss
TVD	Total voltage deviation
TOT	Total operating time of relays
P_{Loss}, Q_{Loss}	Total power losses
R_{ij}, Z_{ij}	Line resistance and impedance
P_{ij}, Q_{ij}	Powers in branch i_j
P_i, Q_i	Powers at bus i

P_G, Q_G	Powers of sub-station	$S_{\max}$	Maximum apparent power
P_D, Q_D	Powers of load demand	N_{bus}	Bus number
P_{PVDG}	Injected power from PVDG units	$\mathrm{PVDG}_{Position}$	PVDG unit position
$V_{\min}$, $V_{\max}$	Bus voltage's limit	N_{PVDG}	PVDG unit number
$\Delta V_{\max}$	Maximum voltage drops	$N_{\mathrm{PVDG} \times \max}$	PVDG unit maximum number
S_{ij}	Apparent power in branch	n_{PVDG}	PVDG unit location

References

[1] Jung, J., Onen, A., Arghandeh, R., Broadwater, R. P. "Coordinated control of automated devices and photovoltaic generators for voltage rise mitigation in power distribution circuits", Renewable Energy, 66, pp. 532–540, 2014.
https://doi.org/10.1016/j.renene.2013.12.039

[2] Karimi, M., Mokhlis, H., Naidu, K., Uddin, S., Bakar, A. H. A. "Photovoltaic penetration issues and impacts in distribution network – A review", Renewable and Sustainable Energy Reviews, 53, pp. 594–605, 2016.
https://doi.org/10.1016/j.rser.2015.08.042

[3] Katiraei, F., Agüero, J. R. "Solar PV integration challenges", IEEE Power and Energy Magazine, 9(3), pp. 62–71, 2011.
https://doi.org/10.1109/MPE.2011.940579

[4] Gandhi, O., Kumar, D. S., Rodríguez-Gallegos, C. D., Srinivasan, D. "Review of power system impacts at high PV penetration Part I: Factors limiting PV penetration", Solar Energy, 210, pp. 181–201, 2020.
https://doi.org/10.1016/j.solener.2020.06.097

[5] van der Walt, H. L. R., Bansal, R. C., Naidoo, R. "PV based distributed generation power system protection: A review", Renewable Energy Focus, 24, pp. 33–40, 2018.
https://doi.org/10.1016/j.ref.2017.12.002

[6] Meskin, M., Domijan, A., Grinberg, I. "Impact of distributed generation on the protection systems of distribution networks: analysis and remedies – review paper", IET Generation, Transmission & Distribution, 14(24), pp. 5944–5960, 2020.
https://doi.org/10.1049/iet-gtd.2019.1652

[7] Katyara, S., Staszewski, L., Leonowicz, Z. "Protection coordination of properly sized and placed distributed generations–methods, applications and future scope", Energies, 11(10), 2672, 2018.
https://doi.org/10.3390/en11102672

[8] Manditereza, P. T., Bansal, R. "Renewable distributed generation: The hidden challenges – A review from the protection perspective", Renewable and Sustainable Energy Reviews, 58, pp. 1457–1465, 2016.
https://doi.org/10.1016/j.rser.2015.12.276

[9] Akmal, M., Al-Naemi, F., Iqbal, N., Al-Tarabsheh, A., Meegahapola, L. "Impact of distributed PV generation on relay coordination and power quality", In: 2019 IEEE Milan PowerTech, Milan, Italy, 2019, pp. 1–6. ISBN 978-1-5386-4723-3
https://doi.org/10.1109/PTC.2019.8810791

[10] Jia, K., Gu, C., Xuan, Z., Li, L., Lin, Y. "Fault characteristics analysis and line protection design within a large-scale photovoltaic power plant", IEEE Transactions on Smart Grid, 9(5), pp. 4099–4108, 2018.
https://doi.org/10.1109/TSG.2017.2648879

[11] Alcala-Gonzalez, D., García del Toro, E. M., Más-López, M. I., Pindado, S. "Effect of distributed photovoltaic generation on short-circuit currents and fault detection in distribution networks: a practical case study", Applied Sciences, 11(1), 405, 2021.
https://doi.org/10.3390/app11010405

[12] Zeineldin, H. H., Mohamed, Y. A.-R. I., Khadkikar, V., Pandi, V. R. "A protection coordination index for evaluating distributed generation impacts on protection for meshed distribution systems", IEEE Transactions on Smart Grid, 4(3), pp. 1523–1532, 2013.
https://doi.org/10.1109/TSG.2013.2263745

[13] Patel, K., Arif, M. T., Saha, S., Aktarujjaman, M. "Investigation of renewable energy-based DG impacts on protection relay operation", In: 2019 29th Australasian Universities Power Engineering Conference (AUPEC), Nadi, Fiji, 2019, pp. 1–6. ISBN 978-1-7281-5044-4
https://doi.org/10.1109/AUPEC48547.2019.211974

[14] Aghdam, T. S., Karegar, H. K., Zeineldin, H. H. "Transient stability constrained protection coordination for distribution systems with DG", IEEE Transactions on Smart Grid, 9(6), pp. 5733–5741, 2018.
https://doi.org/10.1109/TSG.2017.2695378

[15] Aghdam, T. S., Karegar, H. K., Zeineldin, H. H. "Variable tripping time differential protection for microgrids considering DG stability", IEEE Transactions on Smart Grid, 10(3), pp. 2407–2415, 2019.
https://doi.org/10.1109/TSG.2018.2797367

[16] Kar, S., Samantaray, S. R. "Impact of microgrid operation on the performance of overcurrent relay coordination and assessment of differential relay coordination", Electric Power Components and Systems, 48(9-10), pp. 1049–1062, 2020.
https://doi.org/10.1080/15325008.2020.1825550

[17] Cintuglu, M. H., Ma, T., Mohammed, O. A. "Protection of autonomous microgrids using agent-based distributed communication", IEEE Transactions on Power Delivery, 32(1), pp. 351–360, 2017.
https://doi.org/10.1109/TPWRD.2016.2551368

[18] Ahmad, N. I., Ab-Kadir, M. Z. A., Izadi, M., Azis, N., Radzi, M. A. M., Zaini, N. H., Nasir, M. S. M. "Lightning protection on photovoltaic systems: A review on current and recommended practices", Renewable and Sustainable Energy Reviews, 82, pp. 1611–1619, 2018.
https://doi.org/10.1016/j.rser.2017.07.008

[19] Gao, H., Li, J., Xu, B. "Principle and implementation of current differential protection in distribution networks with high penetration of DGs", IEEE Transactions on Power Delivery, 32(1), pp. 565–574, 2017.
https://doi.org/10.1109/TPWRD.2016.2628777

[20] Casagrande, E., Woon, W. L., Zeineldin, H. H., Svetinovic, D. "A differential sequence component protection scheme for microgrids with inverter-based distributed generators", IEEE Transactions on Smart Grid, 5(1), pp. 29–37, 2014. https://doi.org/10.1109/TSG.2013.2251017

[21] Wang, M., Yu, J., Zheng, T., Chen, Z., Wen, F., Luo, L. L., Chen, Y. "Mechanism of second harmonic generation of photovoltaic grid-connected system faults and its impact on transformer protection", Energy Reports, 6, pp. 1619–1627, 2020. https://doi.org/10.1016/j.egyr.2020.12.027

[22] Holguin, J. P., Rodriguez, D. C., Ramos, G. "Reverse power flow (RPF) detection and impact on protection coordination of distribution systems", IEEE Transactions on Industry Applications, 56(3), pp. 2393–2401, 2020. https://doi.org/10.1109/TIA.2020.2969640

[23] Snodgrass, J., Xie, L. "Overvoltage analysis and protection of lightning arresters in distribution systems with distributed generation", International Journal of Electrical Power & Energy Systems, 123, 106209, 2020. https://doi.org/10.1016/j.ijepes.2020.106209

[24] Li, S., Chen, H., Wang, M., Heidari, A. A., Mirjalili, S. "Slime mould algorithm: A new method for stochastic optimization", Future Generation Computer Systems, 111, pp. 300–323, 2020. https://doi.org/10.1016/j.future.2020.03.055

[25] El Sehiemy, R. A., Selima, F., Bentouati, B., Abido, M. A. "A novel multi-objective hybrid particle swarm and salp optimization algorithm for technical-economical-environmental operation in power systems", Energy, 193, 116817, 2020. https://doi.org/10.1016/j.energy.2019.116817

[26] IEEE "1729-2014 - IEEE recommended practice for electric power distribution system analysis", Institute of Electrical and Electronics Engineers, New Jersey, NJ, USA, 2014. https://doi.org/10.1109/IEEESTD.2014.6974967

[27] IEEE "C57.12.70-2020 - IEEE standard for standard terminal markings and connections for distribution and power transformers", Institute of Electrical and Electronics Engineers, New Jersey, NJ, USA, 2020. https://doi.org/10.1109/IEEESTD.2020.9208013

[28] IEEE "2781-2022 - IEEE guide for load modeling and simulations for power systems", Institute of Electrical and Electronics Engineers, New Jersey, NJ, USA, 2022. https://doi.org/10.1109/IEEESTD.2022.9905546

[29] Zellagui, M., Lasmari, A., Settoul, S., El-Bayeh, C. Z., Belbachir, N. "Arithmetic optimization algorithm for optimal installation of DSTATCOM into distribution system based on various voltage stability indices", In: 2021 9th International Conference on Modern Power Systems (MPS), Cluj-Napoca, Romania, 2021, pp. 1–6. ISBN 978-1-6654-3383-9 https://doi.org/10.1109/MPS52805.2021.9492572

[30] Belbachir, N., Zellagui, M., Settoul, S., El-Bayeh, C. Z. "Multi-objective optimal renewable distributed generator integration in distribution systems using grasshopper optimization algorithm considering overcurrent relay indices", In: 2021 9th International Conference on Modern Power Systems, Cluj-Napoca, Romania, 2021, pp. 1–6. ISBN 978-1-6654-3383-9 https://doi.org/10.1109/MPS52805.2021.9492567

[31] Belbachir, N., Zellagui, M., Settoul, S., El-Bayeh, C. Z., El-Sehiemy, R. A. "Multi dimension-based optimal allocation of uncertain renewable distributed generation outputs with seasonal source-load power uncertainties in electrical distribution network using marine predator algorithm", Energies, 16(4), 1595, 2023. https://doi.org/10.3390/en16041595

[32] Belbachir, N., Zellagui, M., Lasmari, A., El-Bayeh, C. Z., Bekkouche, B. "Optimal PV sources integration in distribution system and its impacts on overcurrent relay-based time-current-voltage tripping characteristics", In: 2021 12th International Symposium on Advanced Topics in Electrical Engineering (ATEE), Bucharest, Romania, 2021, pp. 1–7. ISBN 978-1-6654-4807-9 https://doi.org/10.1109/ATEE52255.2021.9425155

[33] Belbachir, N., Zellagui, M., Lasmari, A., El-Bayeh, C. Z., Bekkouche, B. "Optimal integration of photovoltaic distributed generation in electrical distribution network using hybrid modified PSO algorithms", Indonesian Journal of Electrical Engineering and Computer Science, 24(1), pp. 50–60, 2021. http://doi.org/10.11591/ijeecs.v24.i1.pp50-60

[34] Saleh, K. A., Zeineldin, H. H., Al-Hinai, A., El-Saadany, E. F. "Optimal coordination of directional overcurrent relays using a new time-current-voltage characteristic", IEEE Transactions on Power Delivery, 30(2), pp. 537–544, 2015. http://doi.org/10.1109/TPWRD.2014.2341666

[35] Bayati, N., Dadkhah, A., Sadeghi, S. H. H., Vahidi, B., Milani, A. E. "Considering variations of network topology in optimal relay coordination using time-current-voltage characteristic", In: 2017 IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe), Milan, Italy, 2017, pp. 1–5. ISBN 978-1-5386-3918-4 https://doi.org/10.1109/EEEIC.2017.7977810

[36] Momesso, A. E. C., Bernardes, W. M. S., Asada, E. N. "Fuzzy adaptive setting for time-current-voltage based overcurrent relays in distribution systems", International Journal of Electrical Power & Energy Systems, 108, pp. 135–144, 2019. https://doi.org/10.1016/j.ijepes.2018.12.035

[37] Yazdaninejadi, A., Nazarpour, D., Golshannavaz, S. "Sustainable electrification in critical infrastructure: Variable characteristics for overcurrent protection considering DG stability", Sustainable Cities and Society, 54, 102022, 2020. https://doi.org/10.1016/j.scs.2020.102022

[38] Yazdaninejadi, A., Golshannavaz, S. "Robust protection for active distribution networks with islanding capability: An innovative and simple cost-effective logic for increasing fault currents virtually", International Journal of Electrical Power & Energy Systems, 118, 105773, 2020. https://doi.org/10.1016/j.ijepes.2019.105773

[39] MathWorks "MATLAB software, (R2022b)", [computer program] Available at: https://www.mathworks.com/products/matlab.html [Accessed: 01 July 2022]