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An Investigation of the Impact of Distributed Generation Penetration on Directional Overcurrent Relay Coordination in a Distribution Network

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Keywords

DOCR Coordination
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Power Loss Reduction
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Abstract

Distributed generation units (DGs) are rapidly becoming widespread in distribution systems due to their advantages such as power loss reduction, voltage profile improvement, and economic returns. Many researchers seek new ways to maximize their these advantages. However, their impact on the fault current is a problem for the field of power system protection. The changes in the short-circuit currents due to DGs cause the miscoordination of the directional overcurrent relays (DOCRs). In this paper, the impact of distribution generation penetration on DOCR coordination is analyzed and investigated. Besides this negative impact of DGs, their contributions to reducing power loss and improving the voltage profile are also analyzed for different DG penetration levels. The gazelle optimization algorithm is utilized to solve the DOCR coordination problem studied in this paper. The method is performed on the distribution section of the IEEE 14-bus system. It is seen that a significant number of miscoordinations occur when even the DG penetration is increased by about 10%. With the increase in DG penetration, the number of miscoordinations does not increase proportionally, but there is a proportional increase in active and reactive power loss reduction and voltage profile improvement.

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1. INTRODUCTION

Power system protection is being studied intensively by researchers as an important issue in order to deliver energy to consumers in a reliable way, to prevent damage to the power system due to possible short-circuit faults, and to avoid unnecessary energy interruptions in case of short-circuit faults. Among the power system protection elements, relays play the most important role in detecting the fault and taking the necessary action against the fault. Especially directional overcurrent relays (DOCRs) are commonly used in transmission and distribution networks due to their economic advantages (Shih et al., 2014). Directional overcurrent relays can be used for both primary (main) protection and secondary (backup) protection duties in power systems. The purpose of secondary protection is to provide a backup protection mechanism against failures that may occur in primary protection (Perveen et al., 2016). The important point here is that a certain time difference between the operating times of the relays in the primary and secondary protection duties, which is called coordination time interval (CTI), should be preserved for all relay pairs in the power system (Ayvaz, 2022). The CTI value is usually taken into account as a minimum of 0.3 seconds for electromechanical relays and a minimum of 0.1 seconds for digital relays. The main aim of solving the DOCR coordination problem is to reach the minimum total operating time of the relays without any violation of CTI values for all relay pairs.

The DOCR coordination problem is a non-linear optimization problem that has been solved by several optimization methods. These methods can be classified as mathematical programming methods, meta-heuristic

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methods, and hybrid methods. Considering the recent studies, meta-heuristic optimization methods are popular methods that have been utilized to solve the DOCR coordination problem. Some of them are seagull optimization algorithm (SOA) (Abdelhamid et al., 2022), slime mould algorithm (SMA) (Draz et al., 2021), and jaya algorithm (JA) (Yu et al., 2019). The difficulty of solving the DOCR problem can be changeable based on the power system structure. For example, in radial systems, one relay in secondary protection generally corresponds to one relay in primary protection duty. This is different for meshed systems and more than one relay can be used for backup protection.

Distributed generation units (DGs) are used in distribution networks in renewable and non-renewable forms. Further, they can be classified according to their connection types as synchronous and inverter-based. Especially synchronous DGs have the most important position in the field of power system protection (Saleh et al., 2015). The effect of synchronous DGs on the fault current is much more than the inverter-based DGs (Ayvaz & Istemihan Genc, 2020). The synchronous DGs can change the direction and magnitude of the fault currents and cause the miscoordination of relays. In the literature, there are many published studies that propose new approaches to solve the DOCR coordination problem for distribution networks with DGs. The study carried out by Elmitwally et al. (2020) aims to find the optimal locations and sizes of fault current limiting devices taking into account the DOCR coordination on a power system with DGs. Narimani and Hashemi-Dezaki (2021) propose a new coordination method considering the stability of DGs. However, to the best of the Author's opinion, no study analyzes the number of DOCR coordination violations, power loss reduction, and voltage profile improvement for different DG penetration levels.

In this paper, an investigation study is proposed to analyze the impact of DG penetration on DOCR coordination, reduction in active and reactive power losses, and voltage profile improvement for a distribution network. To solve the DOCR coordination problem studied in this paper, the gazelle optimization algorithm (GOA) (Agushaka et al., 2023) is used. GOA is a recent meta-heuristic method inspired by the survival behavior of gazelles. GOA has been used for solving many other engineering problems, i.e. data clustering (Abualigah et al., 2022), and has shown superior performance.

The rest of the paper is organized as follows: the DOCR coordination problem formulation, power loss calculation function, and voltage deviation function are given in Section 2, the optimization results and the investigations based on these results are presented in Section 3, and Section 4 provides the conclusions.

2. MATERIAL AND METHOD

The objective function of the DOCR coordination problem considered in this study is given by (1).

$$OF = \sum_{m} \sum_{k=1}^{N} T_{k,m} \tag{1}$$

where, N is the total relay number in the distribution network. $T_{k,m}$ are the operation time of the relay k for the fault case m, respectively, and is calculated by using (2).

$$T_{k,m} = TMS_k \times \frac{\alpha}{\left({I_{f_m}}/{PS_k}\right)^{\beta} - \gamma} \tag{2}$$

where, I_{f_m} is the fault current passing through the relay k for the fault case m, TMS_k expresses the time multiplier setting parameter of the relay k, and $\alpha, \beta,$ and γ are constants that determine the relay characteristic and take the values 0.14, 0.02, and 1, respectively, in general (Yu et al., 2019). PS_k is the time multiplier setting of the relay r.

The constraints of the DOCR problem are presented in (3)-(6).

$$CTI \leq T^{backup} - T^{main} \tag{3}$$

$$T_k^{min} \leq T_k \leq T_k^{max} \tag{4}$$

$$PS_k^{min} \leq PS_k \leq PS_k^{max} \tag{5}$$

$$TMS_k^{min} \leq TMS_k \leq TMS_k^{max} \tag{6}$$

The DOCR problem given by (1)-(6) is solved for a base DG penetration level using the gazelle optimization algorithm. This solution gives the optimal relay parameters, i.e. PS_k and TMS_k for all the relays in the system. Once the optimal solution is obtained for the base DG penetration level, i.e. 10% of the system's total power demand, the number of violations in DOCR coordination can be obtained for higher DG penetration levels to investigate the impact of DG penetration on the DOCR coordination. Further, the system's voltage profile and power loss are also obtained and analyzed for different DG penetration levels. Then, the variations in voltage profile, power loss, and the violation number corresponding to the increased DG penetration level are compared and investigated. To investigate the voltage profile improvement numerically, the voltage deviation function, as defined in (7), is used.

$$VD = \sum_{i=1}^{N_B} (1 - |V_i|)^2 \tag{7}$$

where, V_i is the voltage of i^{th} bus (p.u.) and N_B is the number of buses in the power system.

On the other hand, the active and reactive power loss calculation formulas are given in (8) and (9), respectively.

$$\Delta P_{loss} = \sum P_{G\_tot} - \sum P_{D\_tot} \tag{8}$$

$$\Delta Q_{loss} = \sum Q_{G\_tot} - \sum Q_{D\_tot} \tag{9}$$

where, P_{G_tot}, P_{D_tot}, Q_{G_tot} and Q_{D_tot} are the total active power generation, total active power demand, total reactive power generation, and total reactive power demand in the system, respectively.

3. RESULTS AND DISCUSSION

The proposed study is performed on the distribution section of the IEEE 14-bus test system. The detailed system data can be found on the website Christie (1993). The system is modified by adding DGs to buses 6 and 7. The single-line diagram of the modified system is shown in Figure 1. It is assumed that each DG is synchronous type, has 5 MVA capacity, is normally operated at 0.9 at a lagging power factor, and has a 10% transient reactance. The total DG penetration is 10 MVA which corresponds to almost 10% of the total power demand of the system. In addition, each of them is connected to the system through a 20 MVA substation transformer with a 5% reactance. The short circuit power of the grid, i.e. slack bus, is assumed to be 500 MVA. The power flow analysis is performed using the Newton-Raphson method. The short-circuit calculations are made assuming a bolted three-phase-to-ground fault at the midpoint of the line. To calculate the fault currents, the bus impedance matrix (Z_{bus}) method is used (Grainger & Stevenson, 1994).

The control parameters of the GOA are used as their recommended settings given in (Agushaka et al., 2023). The maximum iteration number and population size are set to 1000 and 300, respectively. All the simulations and calculations are performed using MATLAB software. The upper and lower bounds of PS_k are calculated as follows (Fayoud et al., 2022):

$$1.25 \times I_{max\_load} \leq PS_k \leq (2/3) \times I_{min\_sc} \tag{10}$$

where, I_{min_sc} and I_{max_load} are the minimum fault current and maximum load current passing through the relay k, respectively. PS_k^{min} and PS_k^{max} are considered 0.5 and 2.5, respectively. TMS_k^{min} and TMS_k^{max} are set to 0.05 and 1.1, respectively. The current transformer ratio of relays (R1, R2, R3, R6, R7, R10, R12, R13, R14, R16) and (R4, R5, R8, R9, R11, R15) is considered to be 300:1 and 100:1, respectively. For all the relay pairs, CTI is selected for 0.1 seconds.

In Table 1, the short circuit results are given for all the relay pairs. Since the pickup current of the backup relays R10 and R16 are higher than 2/3 of the fault currents passing through them, the corresponding relay pairs in Table 1 are ignored. Using the fault currents given in Table 1, the problem given by (1)-(6) is solved. The optimization results are presented in Table 2. The convergence curve of GOA for searching the minimum total relay operating time is seen in Figure 2. The total operating time is 22.9557 sec and there is no coordination violation for 10% DG penetration as a base case. Besides this level of DG penetration, 20% and 30% DG penetration levels are also considered for the investigations and analyses. The values of evaluation metrics considered in this study are given in Table 3 for different DG penetration levels. According to Table 3, the violation number of coordination is 7 and 8 for 20% and 30% DG penetration levels, respectively. It should be noted that, for 20% and 30% DG penetration levels, the problem given by (1)-(6) is not solved again and the relay settings obtained for 10% DG penetration level are considered. It can be interpreted that the DG penetration increases cause the higher fault currents and thus the coordination violations occur. Even a 10% change in DG penetration is enough to cause serious violations in coordination. In Table 4, the CTI values of relay pairs for different DG penetration levels are shown. The CTI values increase with the increase of penetration level for some relay pairs while they decrease for others. The relay pairs (R1, R3), (R2, R7), (R4, R2), (R9, R13), (R12, R10), (R14, R6), and (R16, R11) are priority relay pairs that cause coordination violations when the changes in DG penetration occur.

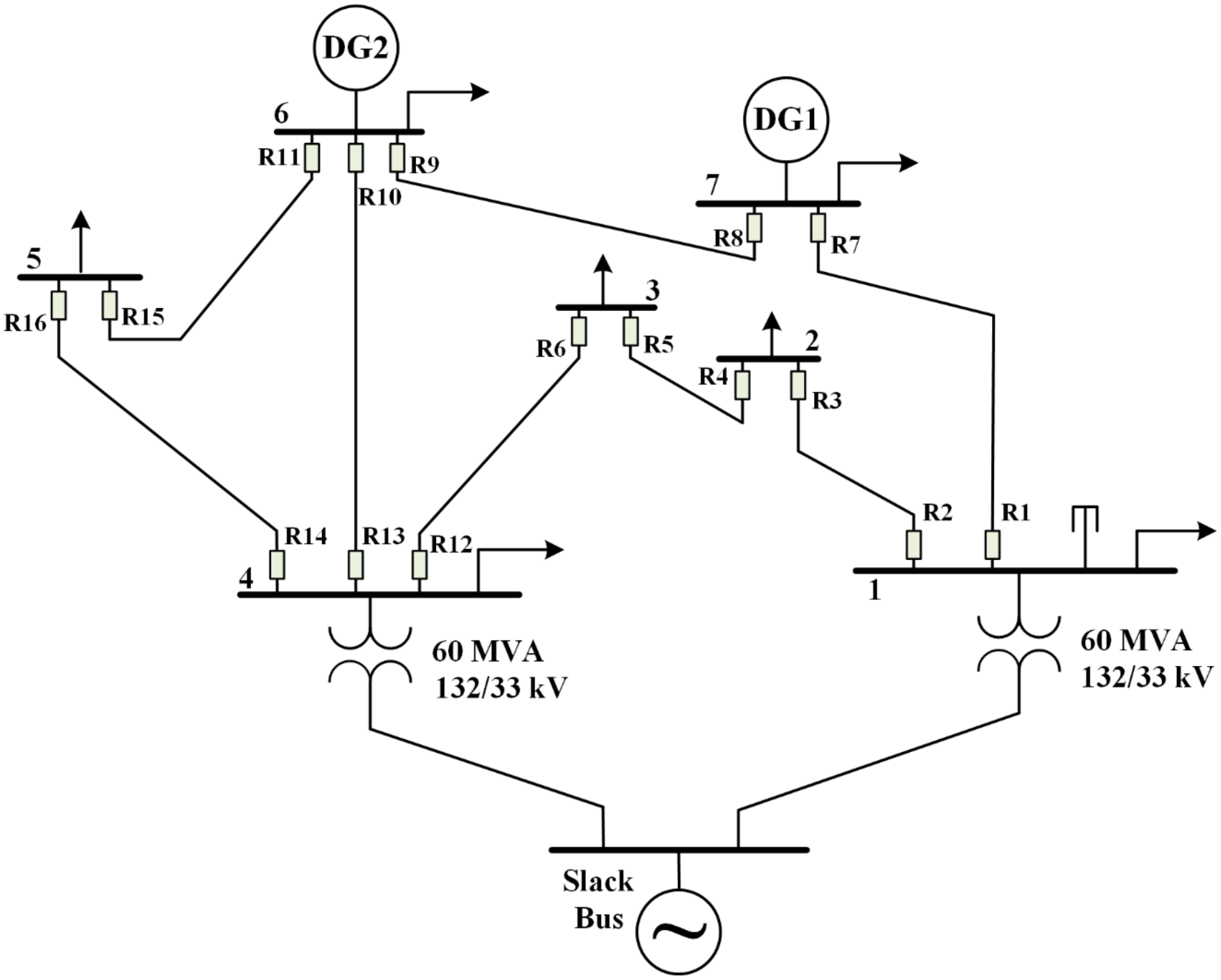

Figure 1. *The modified IEEE 14-bus distribution system*

On the other hand, the total operating time decreases with the increase in DG penetration. This is because the high fault current reduces the relay's operating time according to (1). However, the reduction in total operating time causes the violations in coordination due to the occurrence of CTI values less than 0.1 sec as seen in Table 4. Considering the relay pair (R2, R7), the CTI is 0.8191 sec which is much higher than the limit value of 0.1 sec. However, with a 10% increase in DG penetration, for the relay pair (R2, R7), the CTI takes a negative value, i.e. -0.1248 sec, and a coordination violation occurs. Even this result alone shows the importance of analyzing the DG penetration on relay coordination.

Similar to the total operating time, the voltage deviation and power losses also reduce with the increase in DG penetration. The effect of DG penetration on active power loss is clearly visible. The active power loss reduces from 0.368 to 0.129 MW, which corresponds to a 65% variation when the DG penetration increases from 10% to 30%.

Table 1. *Fault currents passing through the main and backup relays*

Primary Relay	Current of Primary Relay (A)	Backup Relay	Current of Backup Relay (A)
R1	3380	R3	546
R2	4550	R7	948
R3	1311	R5	1311
R4	2906	R2	2906
R5	2115	R12	2115
R6	1599	R4	1599
R7	1790	R9	1133
R8	2048	R1	1442
R9	2663	R13	1680
R9	2663	R15	430
R10	1961	R8	1000
R10	1961	R15	250
R11	3097	R8	932
R11	3097	R13	1561
R12	3833	R10	758
R12	3833	R16	194*
R13	3907	R6	742
R13	3907	R16	220*
R14	3681	R6	678
R14	3681	R10	102*
R15	1596	R14	1596
R16	1224	R11	1224
*2/3 of the current value is lower than the relay's pickup current			

Table 2. *Optimal relay settings*

Relay	**TMS**	**PS**
R1	0.206	0.621
R2	0.296	0.760
R3	0.084	0.782
R4	0.401	0.509
R5	0.325	0.500
R6	0.119	0.560
R7	0.050	2.500
R8	0.187	1.578
R9	0.261	0.700
R10	0.143	0.897
R11	0.125	0.527
R12	0.376	0.500
R13	0.146	1.049
R14	0.222	0.545
R15	0.248	0.500
R16	0.050	0.526
OF (total operating time) = 22.9557 sec		

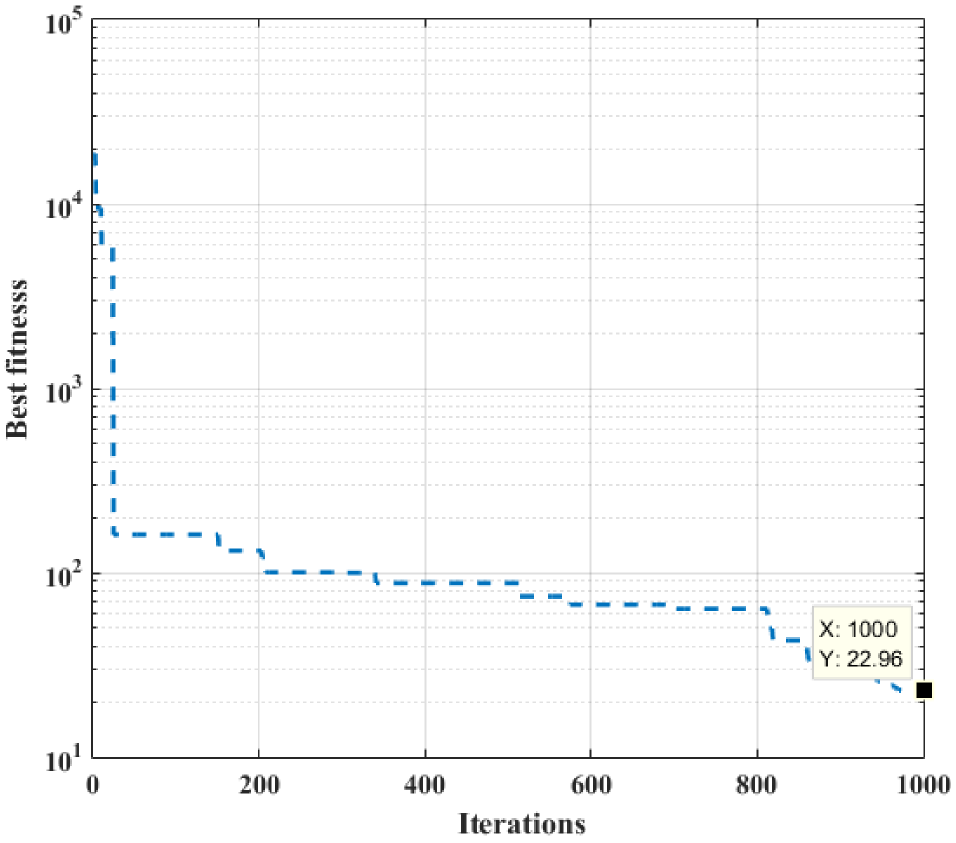

Figure 2. *The GOA convergence curve for searching the minimum total relay operating time*

Table 3. *The evaluation metrics obtained for different DG penetration levels*

Item	**DG Penetration Level**		
	10% (base case)	**20%**	**30%**
The Number of Violations in CTI	0	7	8
OF (sec)	22.9557	22.1752	22.1351
VDI (volt)	0.0120	0.0112	0.0105
ΔP_{loss} (MW)	0.368	0.204	0.129
ΔQ_{loss} (MVAr)	13.265	11.036	10.088

On the other hand, for the same increase that occurred in DG penetration, the voltage deviation reduces from 0.0120 to 0.0105 V, which corresponds to a 13% variation. However, considering the buses in the system individually, it can be interpreted that the increase in DG participation is quite effective in improving the voltage level of some buses. Figure 3 demonstrates the voltage profile of the system for different DG penetrations. The bus numbered 8 is the slack bus. From Figure 3, it is seen that, for buses 4, 5, 6, and 7, the voltage profile is significantly improved by increasing the DG penetration level. Especially considering the DG buses, i.e. buses 6 and 7, the voltage variation is higher than that of others. The numerical and graphical analyses show that power quality problems can be overcome by integrating DGs into modern power systems, especially in terms of voltage deviation and power losses. However, the DGs have a negative impact on protection coordination. For occurring coordination violations, there is no need for the highest DG penetration. Significant violations in coordination may even occur for low DG penetrations. Therefore, there is a need for new approaches to provide reliable DOCR coordination considering the DGs, which are increasingly common in modern power systems.

Table 4. *CTI values of relay pairs for different DG penetration levels*

Primary Relay	**Backup Relay**	**DG Penetration Level**		
		10%	**20%**	**30%**
R1	R3	0.2125	-0.0418	-0.0547
R2	R7	0.8191	-0.1248	-0.2080
R3	R5	0.3351	0.3358	0.3352
R4	R2	0.1277	0.0850	0.0800
R5	R12	0.3833	0.4262	0.4119
R6	R4	0.4231	0.3973	0.3941
R7	R9	0.2395	0.3931	0.4805
R8	R1	0.1900	0.5969	0.8361
R9	R13	0.1167	0.0470	0.0548
R9	R15	0.3038	0.2230	0.2304
R10	R8	0.2024	0.2134	0.2281
R10	R15	0.5644	0.3390	0.2995
R11	R8	0.5198	0.5391	0.5161
R11	R13	0.4233	1.2470	1.8760
R12	R10	0.1731	0.0422	-0.0878
R13	R6	0.1576	0.1012	0.0926
R14	R6	0.1060	0.0474	0.0420
R15	R14	0.1841	0.1281	0.1239
R16	R11	0.1014	0.0868	0.0950

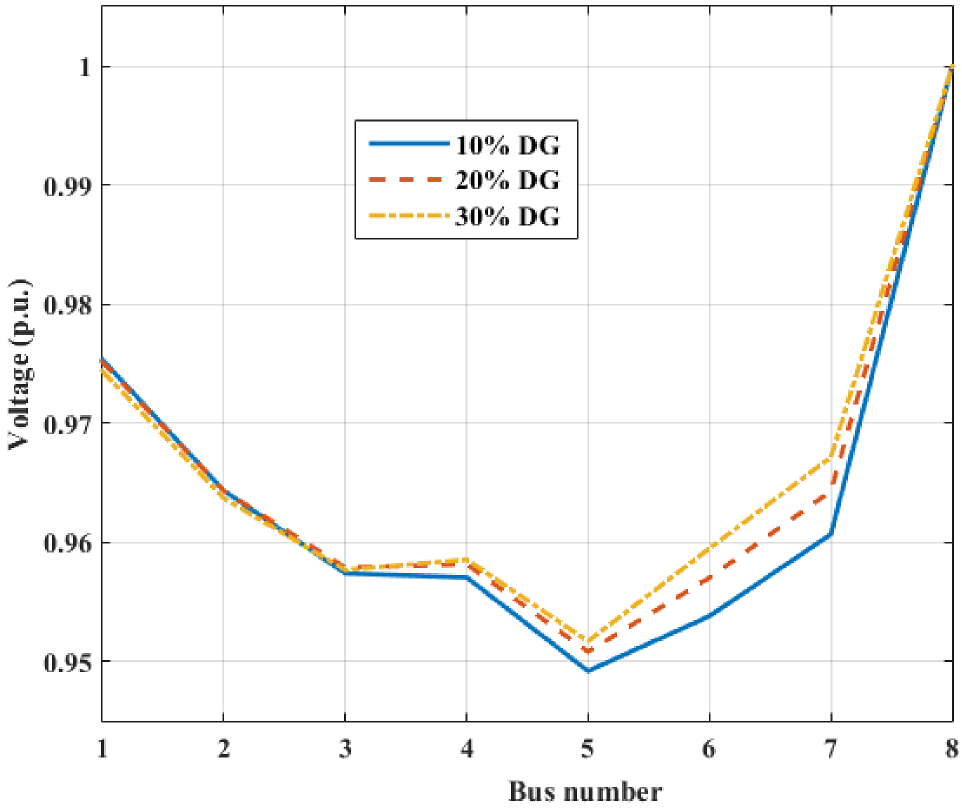

Figure 3. *Voltage profile of the system for different DG penetration levels*

4. CONCLUSION

In this paper, a novel investigation study is performed to evaluate the impact of DG penetration on DOCR coordination and power quality issues. First, the DOCR coordination problem is solved by using the base DG penetration level which corresponds to 10% of the total power demand of the considered distribution system. Based on this solution, the optimal relay settings are found without violating the CTI for all relay pairs. Then, for higher DP penetration levels, the number of coordination violations is obtained. It is shown that even a 10% increase in DG penetration causes a significant number of coordination violations. On the other hand, considering power quality issues, the more the DG penetration is increased, the more the voltage profile is improved and power losses are reduced. To provide reliable and accurate DOCR coordination and to overcome power quality issues, new coordination approaches are needed. The increase in DG penetration should not only be considered as the integration of new DGs into the system but also as intraday fluctuations in the power generation of renewable energy-based DGs. Therefore, there is a need for new DOCR coordination solutions that cover the DG's effect on coordination issues.

CONFLICT OF INTEREST

The author declares no conflict of interest.

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